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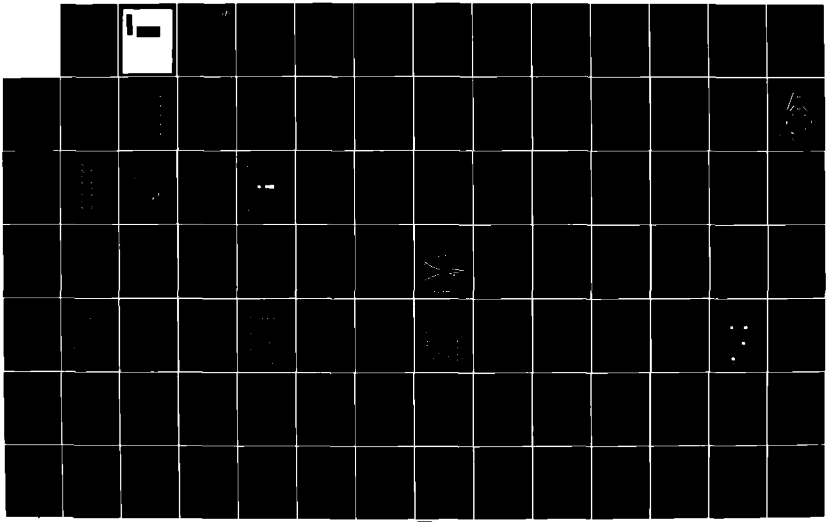

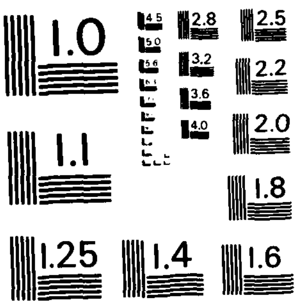

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OVERVIEW OF THE ENGINEERING DESIGN PROCESS WITH REGARD TO HUMAN RESOURCES

Edited by
Malcolm L. Ritchie

1 July 1974

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FINAL REPORT

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HUMAN FACTORS ENGINEERING

DEPARTMENT OF ENGINEERING

WRIGHT STATE UNIVERSITY

DAYTON, OHIO 45431

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FOREWORD

This study has been made possible by a grant from the U.S. Air Force Office of Scientific Research. The grant has been administered by and helpful guidance has been provided by Dr. Charles E. Hutchinson, Assistant Director of Life Sciences.

The work of Wright State University in this effort has been designed to augment and support the program of the U.S.A.F. Human Resources Laboratory, Advanced Systems Division, directed by Dr. Gordon Eckstrand. Frequent coordination meetings have been held with Dr. Eckstrand, Dr. William Askren, and Lt. Col. Edward A. Cope of HRL/AS providing University personnel a background in previous research and problem orientation and access to U.S.A.F. information sources. This guidance and assistance is gratefully acknowledged.

Many individuals in the U.S. Air Force, the U.S. Navy, and the aerospace industry have shared their insights and perspectives.. The Wright State staff expresses its debt of thanks to all of them.

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Section 0.

Introduction, by Malcolm L. Ritchie

The study which this report outlines is aimed at a better understanding of the engineering design process. The reason for wanting this understanding is to be able to influence that design process to get a better balance between hardware and manpower costs.

There is evidence that the manpower costs of supporting the equipment of the U. S. Air Force are increasing. Dr. Gordon Eckstrand, of the Air Force Human Resources Laboratory, reports that product support absorbs 43% of the Air Force budget. The largest share of that cost is maintenance. The total figure is so large that a reduction of 5% would free enough money to buy 125 new F-4 aircraft.

Instead of seeing such a reduction in the near future, Eckstrand sees the support and manpower costs increasing rapidly. The total cost of given hardware systems incurred over their life-cycle now runs four to ten times the cost of acquisition. These data have particular impact for Eckstrand since he has directed a research group for more than 20 years with a charter to develop the knowledge to make Air Force manpower more effective.

Many years ago Eckstrand realized that some of the critical decisions which determine manpower costs in product support are made by engineers in the design of the hardware. Following this realization some of his group's efforts were devoted to producing the kind of data which could be used in the design process to produce a better balance of manpower costs over the life cycle of the equipment. The results of this effort have appeared in a large number of reports which were good enough that they should have been more effective.

One study (Askren, et al., 1971) confirmed that the design process is a key point in controlling manpower costs. This study showed that one design alternative in a trade study involved eight times the support cost of another design in the trade-off.

Another study (Meister, et al., 1966) of the form of human resources data showed that design engineers would use the data if it were in a proper form. The useful form for the data is one which allows the designer to relate manpower design variables directly to the other variables he has under consideration.

It was apparent that the design process is complicated. It soon became apparent that it was little understood.

The present study began with a plan for Wright State University to supplement the Air Force study effort by a research effort on the design process. This study would begin with a general structuring of the design process and work toward detailed study of selected aspects. The work reported here is mainly that of trying to lay out a general view of equipment design and lay the groundwork for subsequent more specific effort which will hope to provide the knowledge needed to make an impact on the design process to allow more rational decisions affecting the life-cycle cost.

Section I.

General Factors Influencing Design

A beginning place for understanding the engineering design process is to understand the engineer himself. The twin keys to distinguishing engineers from other people are selection and training.

In this study we have not addressed the problem of selection. Engineers select themselves by applying for admission to a degree program. It is probably true that those who so apply are quite different in some important respects than the population mean of these characteristics. There are some intriguing problems here for future attention.

Training clearly makes engineers significantly different from other people in ways that are sometimes easy to describe. A start on this description has been made in this study by an analysis of the content of a group of textbooks which are used to teach the design process to engineers. The results of this analysis are in Sections I.A. through I.F.

Another general factor influencing design is the role of company policies affecting design. This factor is described in Section I.G. but is not analyzed in detail.

A very large influence on the process of design of Air Force equipment is that of the System Program office (SPO). It is the function of this office to set the objectives of the design group, to regulate the processes of design, and to evaluate at several stages the output of the design process with respect to the objectives. The direct method for an Air Force agency to influence design is through the SPO. A beginning step to lay out the significant features of the role of the SPO comprises Section I.H.

The Air Force has been working toward the inclusion of support variables in the complex form which trade-offs are made in the design process. Section I.J. notes that this effort is under way. Its treatment is not extensive.

As a part of the logistics support impact upon design, the Air Force is developing a capability to express costs of design alternatives as they will be predicted over the life of the equipment. This technique is in the developing stage and is not yet fully implemented in Air Force design.

Section I.A.

Textbook Definitions of Engineering Design, by John M. Howard

Literature on the engineering design process have proposed as many definitions and descriptions of design as there are authors. However, the definition best suited as a reference for the purposes of this discussion is as follows:

> Engineering Design - the activity where various techniques and scientific principles are employed to make decisions regarding the selection of materials and the placement of these materials to form a system or device which satisfied a set of specified and implied requirements. (Middendorf, 1969, p. 2).

The general design process starts with the recognition of a need and the conception of an idea to satisfy this need. It proceeds with the definition of the problem; establishes a value system of objectives and decision criteria for selection among alternative systems; continues through synthesis and analysis, applying decision making to the alternative designs, and leads to the construction and evaluation of a prototype. It concludes with the effective production and distribution of the system. The process is interactive with many feedback loops in the sense that a general problem-solving cycle is applied repeatedly on problems of smaller scope as the project differentiates by delineation of subsystems.

Design may be simple or enormously complex, mathematical or non-mathematical, easy or difficult; it may involve a trivial problem or one of great importance.

For the purposes of this report the terms design, design student, and design method or process, refer to engineering design unless otherwise stated.

Section I.B.

Review of Engineering Design Textbooks, by John M. Howard

Most of the information on the education of the design engineer came from a review of the literature. This review included an analysis of twenty-two engineering design textbooks.* Their selection as being a representative sample, was based on copyright date (all post 1957), organizational basis and orientation, most frequently referenced in the literature, and availability. The following areas were reviewed for each textbook: organizational basis, orientation, type of system examples, type of design tools, methodology for teaching design, design processes, traits, characteristics and attitudes of the competent design engineer, criteria for system selection, and, the author's emphasis on man-machine (human factors) information.

There appear to be four distinct organizational bases into which engineering design textbooks may be categorized. The first textbook category is "process" oriented in that it provides a comprehensive description of a "generalized" model of the engineering design process. The author usually devotes a single chapter to each individual step of the "generalized" design process. This process usually involves the following five basic steps: (1) problem formulation - definition; (2) detailed problem analysis - including system requirements, input-output variables and constraints; (3) generation of design alternatives; (4) decision - selection of criteria, assignment of relative values, application of trade-off process, and selection of optimum design; and, (5) refinement, evaluation, and construction. A wide variety of large-scale man-machine systems are examplified in these texts, (i.e. transportation, environmental, construction). Several of these texts include a section on man as a design component. The "generalized" criteria, the authors emphasize in the evaluation of design alternatives (in order of importance) were; cost, safety, reliability and ease of maintenance. Several of the reviewed texts in this category were: Krick, 1969, Hill, 1970 and Wilson, I., 1965.

The second category of textbook type is example-oriented in that it describes the analysis of a specific "single thread" (operation on a single input) and/or "high traffic" (multiplex input) system. The type of systems analyzed are mostly of the product, industrial or manufacturing type. A secondary orientation in this type of text is that it is usually directed toward a specific engineering speciality, such as electrical, mechanical or product (small appliance). The authors stressed the following criteria for evaluation of design alternatives: cost, reliability, performance, time, and high novelty or innovation. Some of the reviewed texts that fit into this category were: Brichta, 1970; Chestnut, 1967; and Hall, 1962.

The third category might be called subsystem component design as these texts deal mainly with the design of small components of a system,

*See list of Engineering Design Textbooks, pp. 6 & 7.

such as controls, displays, mechanical gears, etc. Also these texts are directed toward an engineering speciality, like electrical, mechanical or manufacturing. Only one reviewed text fell into this category, Pare, 1963, however, several others contained sections in this area.

The fourth category is a "problem" oriented textbook, devoting the majority of each of its chapters to one specific area (tool) that the author feels is useful in the "art" of designing. Two reviewed texts fall into this category: Chestnut, 1965; and Tribus, 1969; however, nearly all reviewed texts had some chapters dealing with design tools. The following is a listing of the tools receiving the most emphasis in the twenty-two reviewed texts (listed in order of decreasing frequency): probability, modeling, decision theory, optimization theory, computing, statistics, reliability, human engineering, simulation, linear programing, information theory, control theory, servomechanism theory and system logic.

Engineering Design Textbooks *

1. Asimow, Morris, Introduction to Design, Prentice-Hall, Inc. Englewood Cliffs, New Jersey, 1962.

2. Beakley, George C., and Ernest G. Chilton, Introduction to Engineering Design and Graphics, The Macmillan Company, New York, 1973.

3. Brichta, A. M.,and Peter M. Sharp, From Project ?roduction, Pergamon Press, London, 1970.

4. Chestnut, H., System Engineering Tools, John Wi! and Sons, New York, 1965.

5. Chestnut, H., System Engineering Methods, John ınd Sons, New York, 1967.

6. Eckman, Donald P. (ed), Systems: Research and Design, John Wiley and Sons, New York, 1961.

7. Gague, R. M. (ed), Psychological Principles in System Development, Holt, Rinehart and Winston, New York, 1962.

8. Geise, John and Walker W. Holler, Maintainability Engineering, U. S. Army Material Command and Martin Company, Orlando Division, 1965.

9. Goode, Harry H., and Robert E. Machol, System Engineering: an Introduction to the Design of Large-Scale Systems., New York, McGraw-Hill, 1957.

10. Gregg, Gordon L., The Design of Design, The University Press, Cambridge, 1969.

11. Gregory, S. A. (ed), The Design Method, Plenum Press, New York, 1966.

12. Hall, Arthur D., A Methodology for Systems Engineering, D. Van Nostrand Company, Inc., Princeton, N. J., 1962.

13. Harrisberger, Lee, Engineersmanship, A Philosophy of Design, Brooks/ Cole Publishing Company, Belmont, California, a division of Wadsworth Publishing Company, Inc., 1966.

14. Hill, Percy, H., The Science of Engineering Design, Holt, Rinehart and Winston, Inc., New York, 1970.

15. Jones, J. Christopher, Design Methods - Seeds of Human Futures, Wiley-Interscience, a division of John Wiley and Sons, New York, 1970.

16. Krick, E. V., An Introduction to Engineering and Engineering Design, John Wiley & Sons, Inc., New York, 1969.

17. Meredith, Dale D., et al., Design and Planning of Engineering Systems, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1973.

18. Middendorf, William H., Engineering Design, Allyn & Bacon, Inc. Boston, 1969.

19. Pare, Eugene, et al, Introduction to Engineering Design, Holt, Rinehart and Winston, New York, 1963.

20. Tribus, Myron, Rational Descriptions, Decisions and Designs, Pergamon Press, New York, 1969.

21. Wilson, Iva G., Information, Computers, and System Design, John Wiley and Sons, Inc., New York, 1965.

22. Wilson, Warren E., Concepts of Engineering System Design, McGraw-Hill, New York, 1965.

Section I.C.

Textbook Approaches to Engineering Design, by John M. Howard

In the engineering design literature a number of approaches to design are described. Some of these approaches share common characteristics and are classifiable into three or four basic design processes. Other design approaches are pecular to themselves and do not fit into this classification system.

Some of the common characteristics shared by the various approaches to engineering design are: (1) a conceptual process, one in which at least a fragment of a mental plan is necessary before the process can proceed; (2) an iterative problem-solving process, in which there is no unique solution, no correct answer, only several adequate answers, some of which may be identified as "better" than others; (3) an analytical process requiring numerical computation; (4) a deductive process using differentiation by analysis for refinement which is a results-oriented process; (5) an iterative probablistic decision making process which is often interdisciplinary in nature; and, (6) normal operation under the stress of time and cost.

By the nature of the design, the process used will be different depending on: the type, size, number of units, and complexity of the system to be designed; the state of the "art"; the supporting personnel and equipment available to be designed by one person or a team; and, whether the system will be with or without human interface.

The traditional approaches to design are oriented toward the design of components and their influence on the system, rather than toward the system as a whole. New systems designed by these approaches have evolved by incremental improvements in components, by observing failures and shortcomings and gradually making changes to eliminate them.

The research approaches to design are oriented toward the analysis of the system. The design methodology for these approaches is similar to that of the general scientific method for the following: observation--literature review, (identify the problem); hypothesis formulation, (subdivide into components); experimentation, (analyze the components); and conclusion, (recombine the components into the desired system).

The design of new systems by the research approaches has the following shortcomings: (1) since it is an analysis approach this implies already-existing phenomena to be analyzed; (2) it focuses on components rather than on wholeness which very often leads to suboptimizations for the total system; (3) it leads to an over-emphasis on techniques to separate the whole into parts; and, (4) there is an emphasis on analytical tools which can create a gulf between those people (engineers) who possess the technical expertise and those who do not.

The systems approach to design is orientated toward the creation of a total system, yet maintaining an understanding of the interactions of the subsystems. The final working system must be foreseen in all its detail since a prototype must come into being at one time rather than evolve. Of course, evolutionary improvement is still involved as even the most advanced design is based on using already designed, developed, and proven components. The systems method mainly provides a means for the orderly, integrated and timely design of systems, and probably is the most applicable to the design of large-scale man-machine systems.

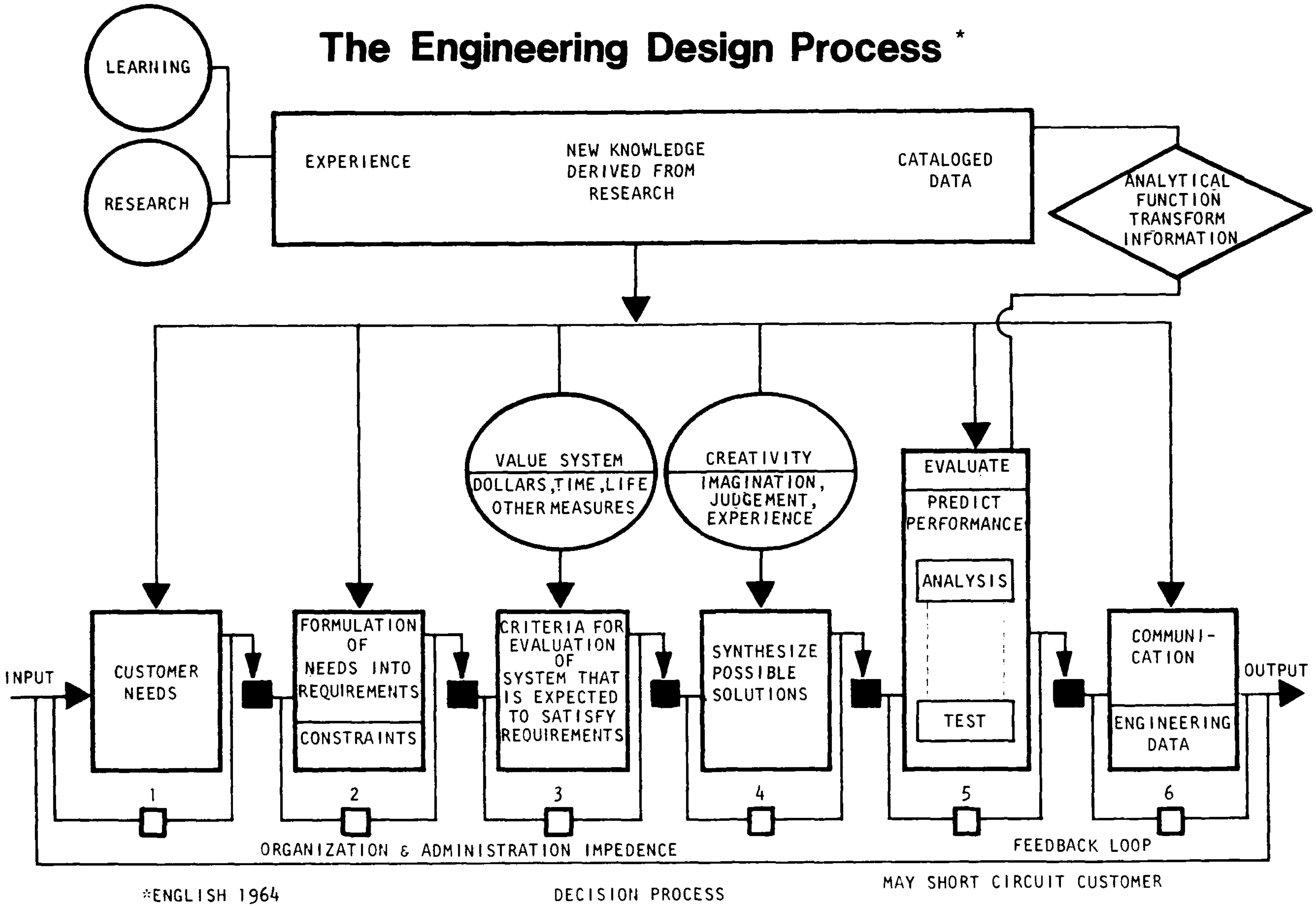
This section attempts to review a general "model" (Figure I.C.1) of the engineering design process, identifying various characteristics and stages that are described in the engineering design literature.

First, looking at the whole process, keep in mind its iterative nature; one simply does not go through the process once, but "loop" repeatedly. Secondly, the process is a decision process in that at each step one is confronted with decisions. Within these two inclusive functions, the process follows six basic steps as depicted by the numbered boxes: (1) the process starts with a need. For the system as a whole, it is usually a customer need; (2) the need must be recognized, identified, and formulated by means of a specific set of requirements. It must be bounded and the constraints must be identified; (3) the criteria for measurement and evaluation of the system must be decided upon to insure that it does satisfy the requirements; Also a value system or "utility function" for performance evaluation needs to be established; (4) synthesize possible system solutions. At this point the design engineer draws on experience in a complex and little understood way and on creativity; (5) having gone through system synthesis, the designer must evaluate the solutions. That is, he must predict its performance in terms of the criteria of step 3 and compare it to the requirements. Two methods, or combinations there of, are useful--analysis and test; and (6) communication--at the outset the design engineer may only need to communicate with himself. As the project unfolds, there is extensive communication with the customer as a feedback to step one--needs. The final communication is the switching out of the complex of loops into the clear output--the design solution.

There are undoubtedly other ways in which engineering design may be described. However, in the judgment of the author, whatever descriptive mode is chosen must contain the elements shown in Figure I.C. 1.

FIGURE I.C.1.

The Engineering Design Process *



*ENGLISH 1964

Section I. D.

Textbook Descriptions of the Design Engineer at Work, by John M. Howard

There are several categories into which design engineers have been classified. The first looks at designers as black boxes. This view of designers is mostly held by the creativity theorists. The designer is believed to work like a magician, receiving external inputs, then letting his cranial system sort through the inputs looking for compatabilities or patterns. Then, "eureka"--the solution is found. This process of design goes on inside the designer's head out of reach of conscious control. Two aids which this designer uses are: (1) brainstorming--a free-association technique which helps to remove inhibitors at the output end; and (2) synectics--this technique sends feedback from the black box output into the black box input using carefully chosen types of analogies. It assists in re-patterning the orginal conflicting inputs until a pattern capable of resolving the conflict emerges.

The following conclusions are drawn about the methods of the designer as a black box: (1) output is governed by the inputs received most recently from the problem and secondly by other inputs received from other problems and experience; (2) output can be enhanced, by relaxing social inhibitors, but with increased randomness of responses; (3) outputs relevant to the problem are dependent upon the time to assimilate and to manipulate the structure of the problem as a whole; and (4) by exercising intelligent control of inputs, relevant outputs will be increased.

The second category looks at designers as glass boxes. Characteristics of this view are: the designer uses externalized thinking based on rational assumptions; the designer has full knowledge of what he is doing and why he is doing it; and the design process is systematic. This design process (Figure I.D.1.)has the following common characteristics: (1) objectives, variables and criteria are fixed in advance; (2) analysis is completed, or at least attempted, before solutions are sought; (3) evaluation is largely linguistic and logical (as opposed to experimental); and, (4) the strategies are usually sequential, and fixed in advance.

For some types of design problems glass box methods are found to work better than the black box approach, whereas, in other cases, they end in confusion, from which the designers revert to their accustomed black box behavior.

The engineering design literature, mostly textbooks lists certain traits and characteristics that the authors feel the competent design engineer should possess. The following is a list of those traits and characteristics most frequently mentioned: creativity, imagination, knowledge of physical sciences, decision making ability, good judgment, inventiveness,

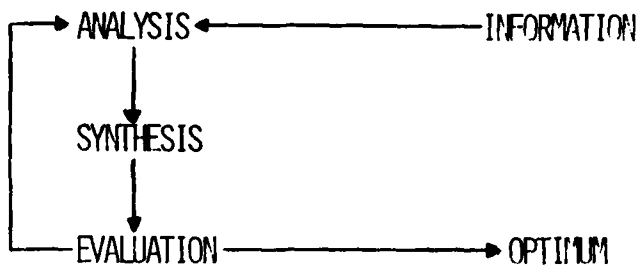


FIGURE I.D.1. GLASS BOX DESIGNERS' DESIGN PROCESS

ability to work with others; skills--such as organization, communication, experimentation, mathematical, and optimization, willingness to assume responsibility, and, a good attitude (questioning, objective, professional, and open-minded).

Likewise, the literature suggests that certain attitudes are required to develop effective design engineers. Whether consciously taught or not most of these attitudes are acquired during the formal engineering design education of the student. Important among these attitudes are: (1) willingness to proceed in the face of incomplete and often contradictory data and incomplete knowledge of the problem; (2) recognition of the necessity of developing and using engineering judgment; (3) a questioning attitude toward every piece of information, every specification, every method, every result; (4) recognition of experiment as the ultimate arbiter; (5) willingness to assume final responsibility for a useful result; and, (6) a willingness to acquire and accept help from outside sources who are specialists on a certain design component (i.e. human interface).

Today's engineering design education with the predominate use of single-answer problems may be having a negative effect on some of these attitudes. Examination of the effect of single-answer problems reveals: (1) that incomplete or contradictory data have little place in this type of problem; (2) engineering judgment is not required of either the student or the instructor, hardly a situation to encourage its development; and, (3) skepticism and the questioning attitude are not encouraged by this situation. Neither the data, the applicability of the method, nor the result are open to question.

Section I.E.

The Education of the Design Engineer, by John M. Howard

The engineering design student is strongly influenced by the engineering design educational system of which he is a product. Certain elements of this system are thought to have the most effect in the shaping of the design engineer's attitudes, design methods and effectiveness. These elements include: the engineering departments' orientation; educational philosophy of the engineering department and the individual faculty; the professor's emphasis on design; the methods used in the teaching of design; the design processes taught; the engineering design textbooks used; and, the design tools taught.

The orientation of the engineering department, be it electrical, mechanical, civil or systems is one of the important influences on the experiences a design student receives. The type of system he learns to design and the design process he learns to use will influence his design approach. For example, if an engineering student studied design in an electrical or mechanical engineering department, the possibility of that future design engineer being exposed to the design of man-machine systems is extremely rare. Instead, the student learns a process for designing small electrical or mechanical components or products, where the user of the product is not a system design element, he is a customer.

The educational philosophy of a specific engineering department orientation is another element suspected to have an effect on design education. Along with the department's philosophy, the philosophy of the individual engineering professor helps to shape the emphasis that is placed on design, the teaching methodology, and the design process.

Each engineering professor uses a specific style or method for the teaching of design. These specific teaching methods are shaped by the individual's education, attitudes and experience. Although, individualistic methods are in use, they generally will fit into one or more of six basic methods for teaching design. The first category is called the traditional approach to teaching design. This method follows the basic "lecture style" of presentation. Meetings are periodic and usually of equal length. Student feedback comes from examinations (written or rarely oral). In the conventional lecture course, all the major decisions are made by the instructor; the choice of goals for the course, the course content, the pace of material, the criteria for progress evaluation. All this encourages student dependency, and postpones independence and the assumption of full responsibility for learning. Thus, the student rarely gets the opportunity to practice democracy. And democratic group work is an important aspect of the engineering design process. Student communication skills

also suffer in this teaching method as there is little incentive to acquire or practice these skills in debate. The communication network is one-way, from the instructor to the student with little feedback. Students who learn to live with authoritarian teaching by conforming and becoming more dependent, sacrifice self-reliance and creativity. However, there are several benefits to this method; such as the presentation of unpublished information, and the coordination of material for better comprehension.

The second category includes the use of programmed instruction as a method for teaching design. This method has been shown to produce good results when the objective is to teach motor and mental skills. Programmed instruction is now beginning to receive attention as an efficient and effective methodology for the teaching of engineering design. However, further experimentation with this method is needed to demonstrate the total usefulness.

The third category involves the use of internship programs in which the design student is taught the design process on the job, by those practicing design. This "learn by doing" method is most commonly found in those colleges with cooperative education programs. Even though this method may be advantageous, with the students learning design from practicing professionals, it may also be perpetuating one of the ills of engineering design education, in that man-machine design is rarely taught.

In the fourth category case history analysis is used for the teaching of design. This approach applies the scientific method to the analysis of both successful and unsuccessful designs. It also provides for good two-way communication channels and feedback between teacher and student.

The fifth category is called t-group (training group). This non-directive method is mainly student-centered instead of being teacher-centered. The method has been proven to be successful where the subject content is human relations and group dynamics; and effective engineering design requires efficient human relations. The t-group method is one of the newer approaches to the teaching of design.

And, the sixth category is a composite of the five preceeding methods. The student-team projects' approach provides interdisciplinary design experiences for the students. This method under the proper guidance has been demonstrated to be a highly successful way for engineering students to learn design; as examplified by the success of the national collegiate urban car design competion.

The problems facing the engineering design education system are numerous. Some of the major short comings of this system are: (1) the engineering design student's awareness and understanding of a design process usually is superficial; (2) there appears to be uneven emphasis in training the design student to handle the different parts of problem-solving. This is evidenced in part by the fact that most of the time spent in educating the design engineer is devoted to systems analysis. Yet, in real life as much time is spent in defining the problem and selecting objectives (requirements). The same appears true of decision making and synthesis. Rarely are decision making and synthesis taught in engineering schools; (3) because of insufficient

stress on systems synthesis, most graduates have little experience in creativity, consequently, they have little confidence that they can be creative; (4) students are deficient in the communication skills, including the skills of listening, speaking and writing; (5) lacking in the training and experience of performing as a team; and, (6) few faculty members are experienced designers.

Section I.F.

Design Textbook Authors on Human Factors as a Design Variable, by John M. Howard

In the review of the twenty-two engineering design textbooks, an analysis of the amount and type of human factors information was made. Included in less than 40% of those texts, was any major reference or description of the human factors involved in the design variables. This is partly a function of the engineering orientation of the texts in that they describe the design for non-human interfaced systems. It is also a function of the attitudes and assumptions the authors make about the value of human factors. These are best summarized in a statement by Middendorf (Middendorf, 1969 p.272) where he states "...the designer must study the characteristics of this element (man) of the system," However, "THIS BACKGROUND IS SO EXTENSIVE THAT WE MUST ASSUME THAT YOU WILL ACQUIRE IT ELSEWHERE".

When human factors information was included in the texts reviewed, it was usually found in the last chapter or two (an indication of relevance!), and delt with the human factors areas of sensory and motor limits of the operator, fatigue, layout, time and motion study. When the terms "manpower or human resources" were referenced, 99% of the time they referred to the general project organization and staff requirements (administration and supervision). There were very few references to maintainability requirements in design.

The following reasons are suggested in the human resources literature for the lack of application of human factors information in the process of engineering design: (1) management attitude; (2) the formal education and formed attitudes of the design engineer; (3) reluctance on the part of the design engineer to try anything new--the design worked before; (4) the inappropriateness or irrelevance or unimportance of much of human factors data; (5) the human factors data format--verbal instead of graphic; (6) timing; (7) quantity of other engineering data; (8) comprehensibility of the data; and (9) a lack of monitoring (follow-up of the human interface performance of the final design in the field.

Despite their rational, common-sense approach to problem-solving, design engineers typically fail to human factor their designs (products) in at least five basic ways: (1) designs for the "average" man; (2) designs for himself; (3) designs for the wrong target population; (4) follows tradition in design; and (5) overgimmicks his design.

Section I.G.

Company Policies Affecting Design, by Malcolm L. Ritchie

Many companies become known for certain design features which appear again and again in their products. One may be known for extra structural strength designed into load-carrying members. Another may be known for extra care in surface finishing of visible parts. Still another may be known for extra comfort or size in crew accommodations.

Such distinctive design features may be due to explicit written policies or they may be due to implicit practices which become accepted design modes. In either case the general environment in which the designer works influences the outcome of the design process by restricting the range of choices which he might make. One company may have an explicit policy which favors the incorporation in design of certain electronic components which it makes. Other companies may have developed a set of strong-willed project engineers who bend men and designs to fit their subjective evaluations of what their products should be, and who have acceded to such power by a succession of successful designs.

In the interviews for this project both types were cited. One subsystem company indicated that its company policies usually helped rough out a good bit of the approach to each product design. One System Program manager described a problem with controlling the design of one of its contractors. After repeated attempts to influence a strong-willed project manager they had to give up and insist that he be replaced. The conclusion was that he would wind-up designing a system much like his last successful one, even though such a design could not fulfill well the current system objectives.

Explicit design policies appear to be much more manageable than the implicit policies or procedures. The explicit ones are more likely to appear as candidates in trade studies against viable alternatives and to undergo quantitative comparisons. It may be difficult to tell when implicit policies are excluding viable alternatives from consideration.

Section I.H.

The Role of the System Program Office, by Malcolm L. Ritchie
(Data from Robert J. Patton of the B1 SPO)

Design as an engineering enterprise involves many different activities performed by many different persons. At one end of the spectrum is a man with a drawing board who makes lines on paper to guide a machinist in cutting metal. At the other end of the spectrum is the chief engineer in the System Program Office. It is his function to see that the Air Force Operational Requirements are defined in such a way that a system may be designed to satisfy them, to guide the general design, to evaluate each step, and finally to test the output product against the operational requirements.

Robert J. Patton, of the B1 System Program Office has described the design process at some length in presentations he has made informally but not yet published. His overall view of the Weapon System Development Cycle is shown in Figure I.H.1. The process begins with the SPO defining the Operational Requirements of the system, which then get translated into Technical Requirements--what the system should be able to do. Weapons systems are then proposed by the contractor, guided by the SPO. These proposed systems are subjected to three interacting activities--analysis, detailed design, and tests. The design is then verified, then the first products are flight tested. On the basis of flight tests the actual performance is compared against the initial Operational Requirements.

Patton says that the history of a given system consists in a continual narrowing down of the possible configurations of the system until there is only one at the moment of the Preliminary Design Review. From there on the number of drawings begins to increase. This process is shown in Figure I.H.2.

The Design Process itself is described as a branching, multiplying activity as shown in Figure I.H.3. The gross and general features are designed first. The fixing of design of a large segment is followed by the design of a number of smaller units involved in the larger. The design proceeds until the smallest units are all designed and their drawings released.

A significant feature of this view of the design process is the time base associated with level of detail. Patton shows that Preliminary Design has been accomplished when design has become successively more detailed to the point at which the major components of aircraft structure are defined. Two more design reviews are phased before all details are designed and released for production.

Patton defines the Systems Engineering Process as consisting of the following elements:

1. Definition of Requirements
2. Identification of Alternatives
3. Evaluation of Alternatives
4. Selection of Approach
5. Documentation of Work
6. Review and Approval to Proceed

These steps will be repeated in sequence as necessary.

He indicates that a great deal needs to be said about the Identification of Alternatives. This step is the natural place to evaluate complexity, life cycle cost, etc. Therefore, when you are so evaluating you need alternatives which range from the simplest to meet the requirements to the most advanced permitted by the state-of-the-art. Only then can you be sure of encompassing the best choice.

Patton followed these descriptions with an outline of what he calls the "Real Schedule", Figure I.H.4. Along with the various phases of the design and development procedure is shown the cumulative total of initial drawing releases and final drawing releases. Initial drawing releases reach 100% early in the manufacturing phase but final releases continue until the end of production.

There are three identifiably different ways for a SPO to manage the design process:

1. Detailed design involvement
2. Project engineering
3. Management surveillance

Detailed Design Involvement. In this approach the SPO has engineering personnel which are involved in detailed design at the component level. They guide design by being involved in every design decision. The Gunship and the Sidewinder designs were managed this way. This approach requires a large engineering force with strength in all the required design disciplines.

Project Engineering. In this approach the SPO is active at the subsystem design level. The focus is on interface design. It requires a "systems engineering" force with strengths in interface design and in testing subsystems. For design engineering problems temporary strength can be achieved by calling in consultants on an "ad hoc" basis. The B-1, the F-111, and the F-15 are examples of designs using this procedure. In the B-1 program frequent use was made of very competent people in special fields to review the design process.

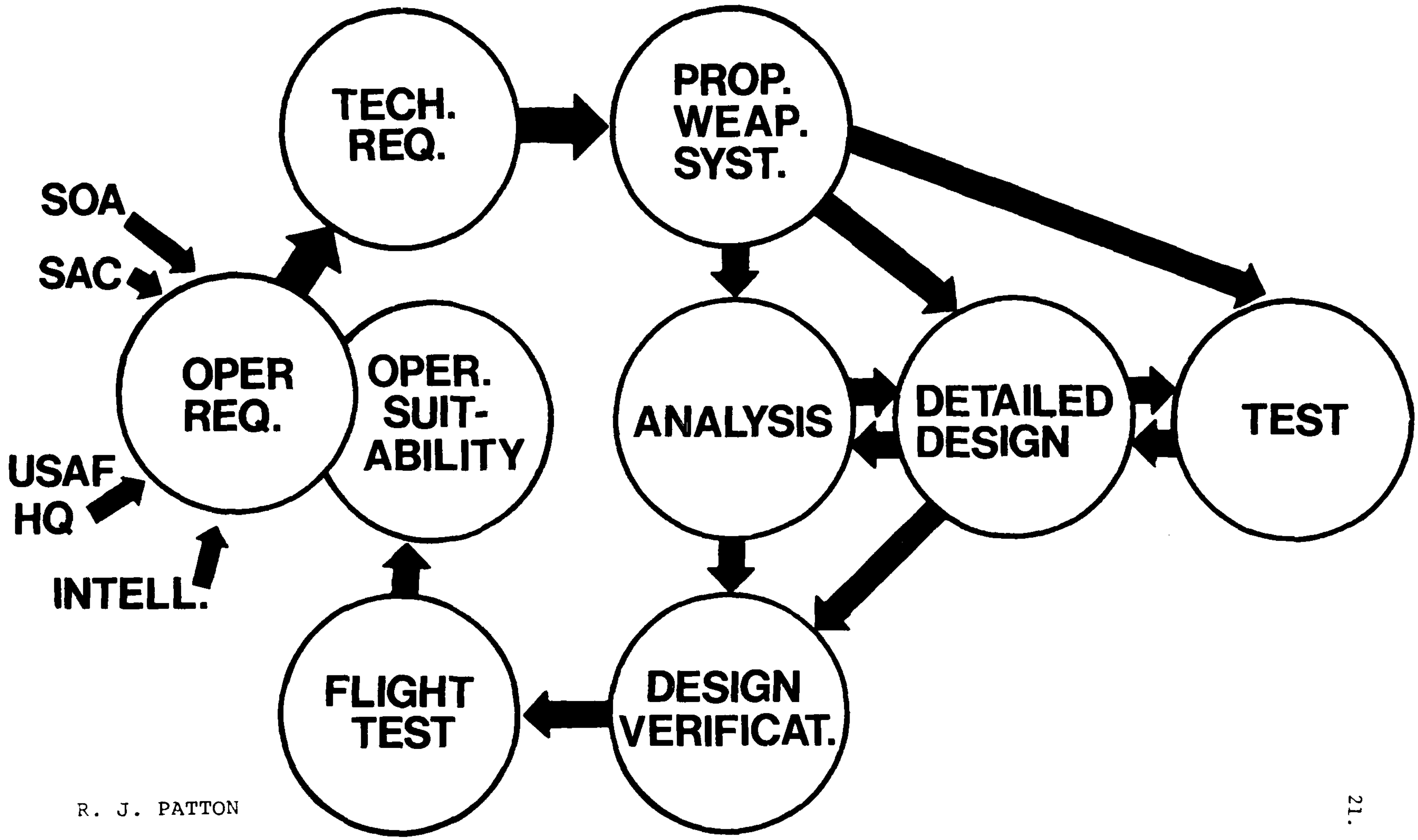
Management Surveillance. In this approach the SPO operation is a system level activity focusing on systems performance. It uses a small but highly competent engineering force which anticipates, then evaluates overall system performance. Examples are the FAA certification procedures and the Black SR-71 program.

One subsystem manufacturer had some critical comments about the way SPO operations affected them. One such comment was that SPO personnel sometimes misapply specifications because they don't understand design. From the SPO viewpoint this same fault may be traced to lack of personnel to perform the job as defined.

Another complaint of the manufacturer was that the SPO is sometimes inconsistent in maintenance philosophy in different requirements on the same system--one area presumming certain ground equipment and another not making that presumption. Another complaint was that maintenance skills have frequently been specified which are inconsistent with the equipment specification.

FIGURE I.H.1.

Weapon System Development Cycle



R. J. PATTON

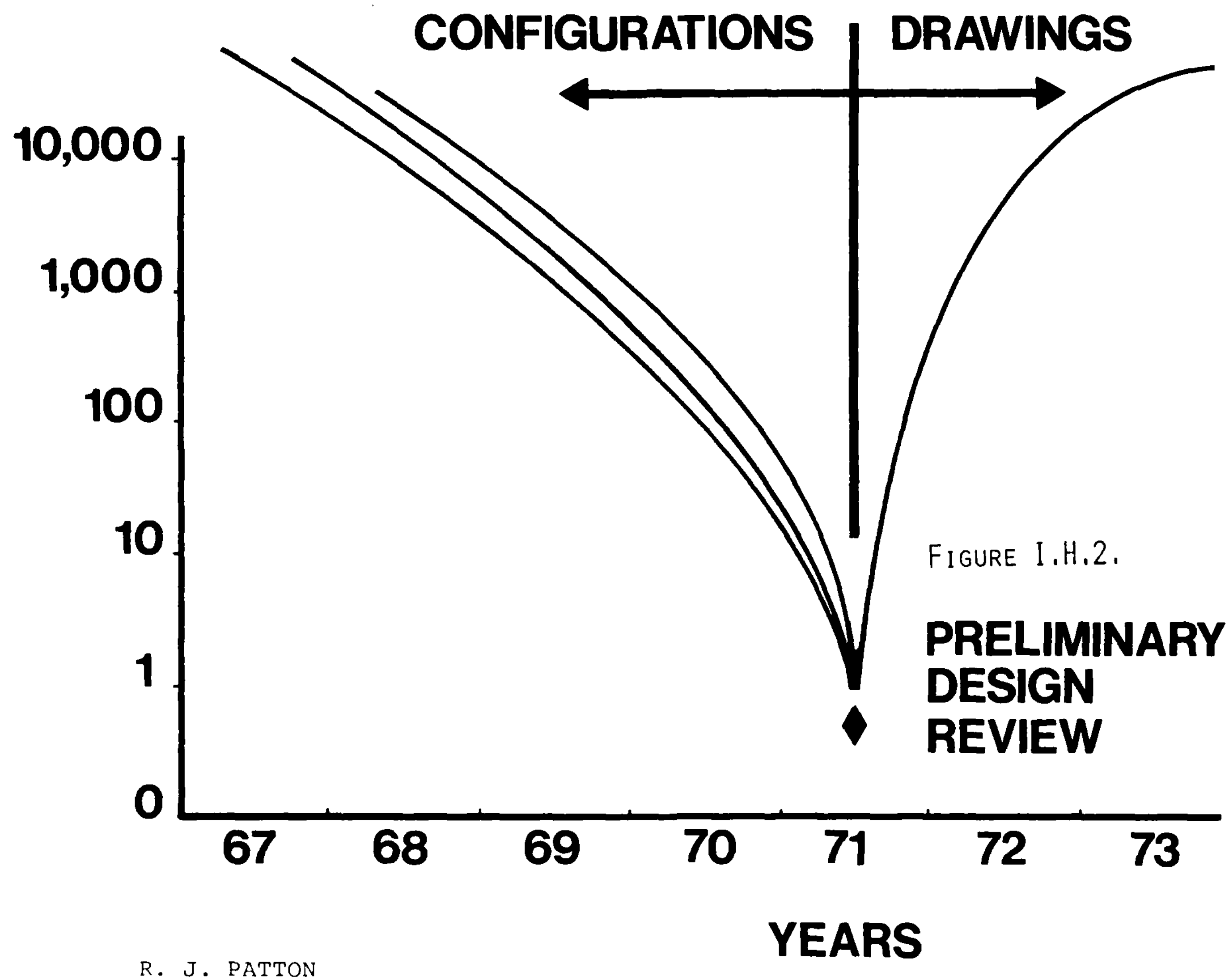
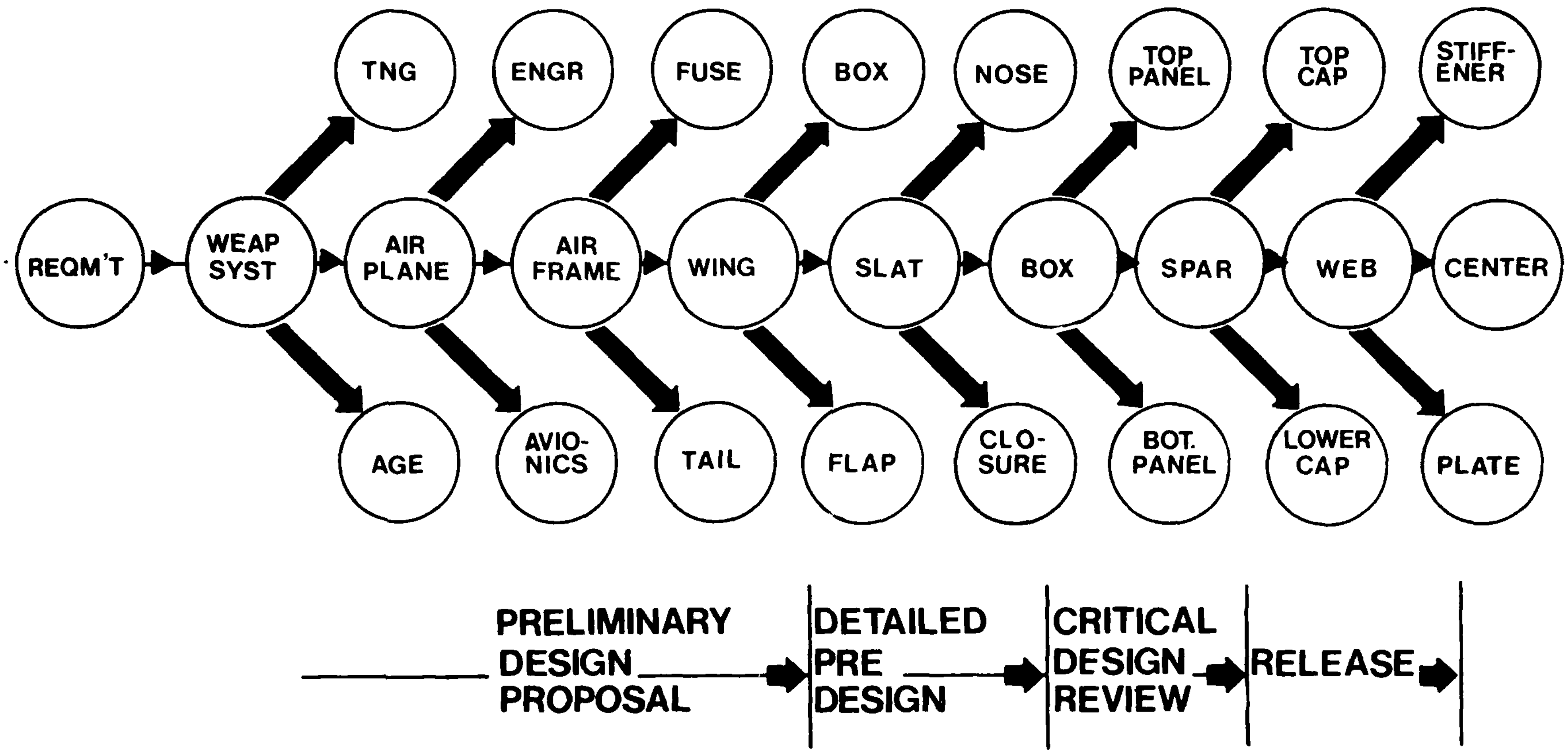


FIGURE I.H.2.

R. J. PATTON

FIGURE I.H.3.

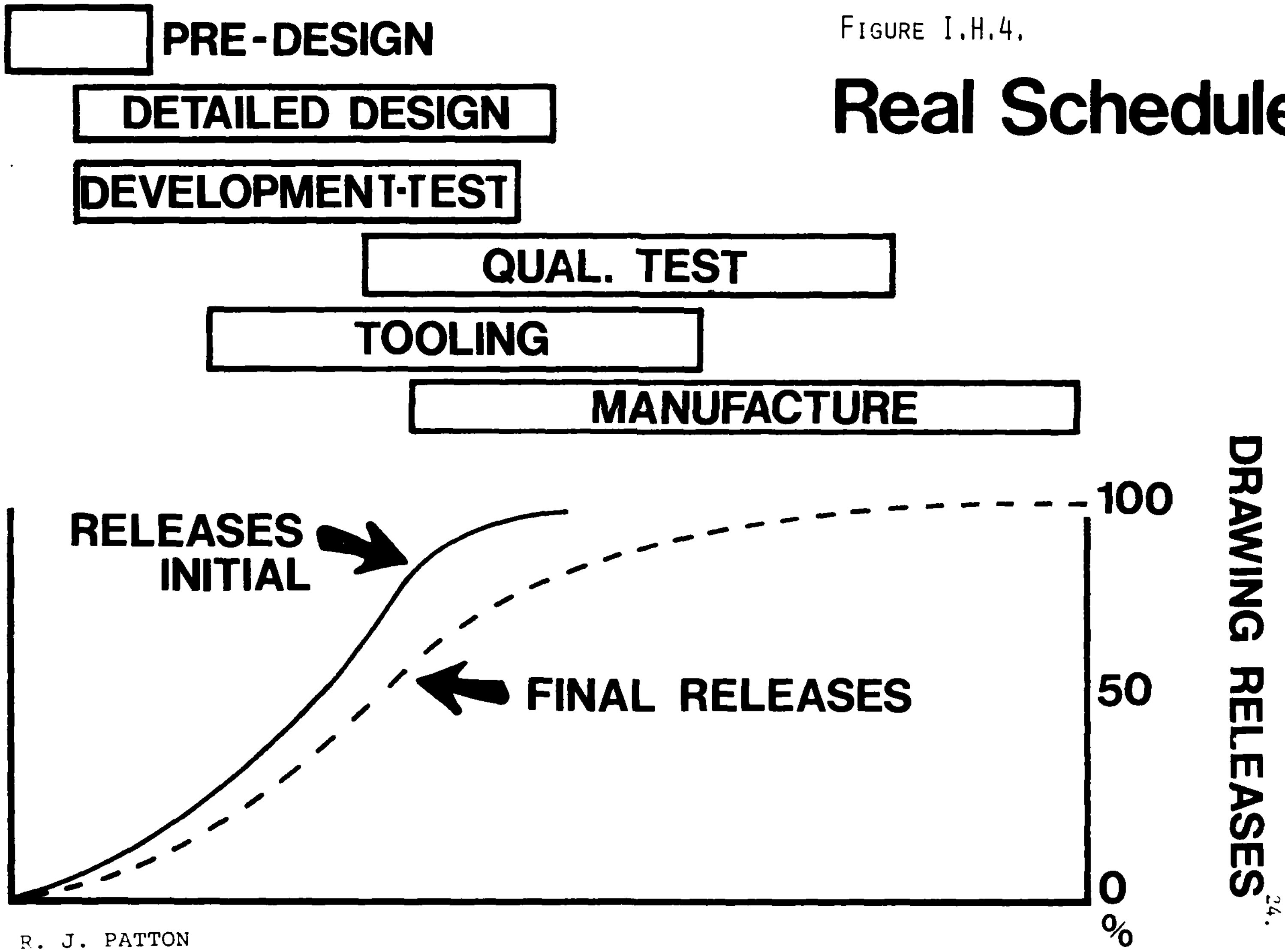
Design Process



R. J. PATTON

Figure I.H.4.

Real Schedule



R. J. PATTON

Section I.J.

Integrated Logistics Support, by Malcolm L. Ritchie

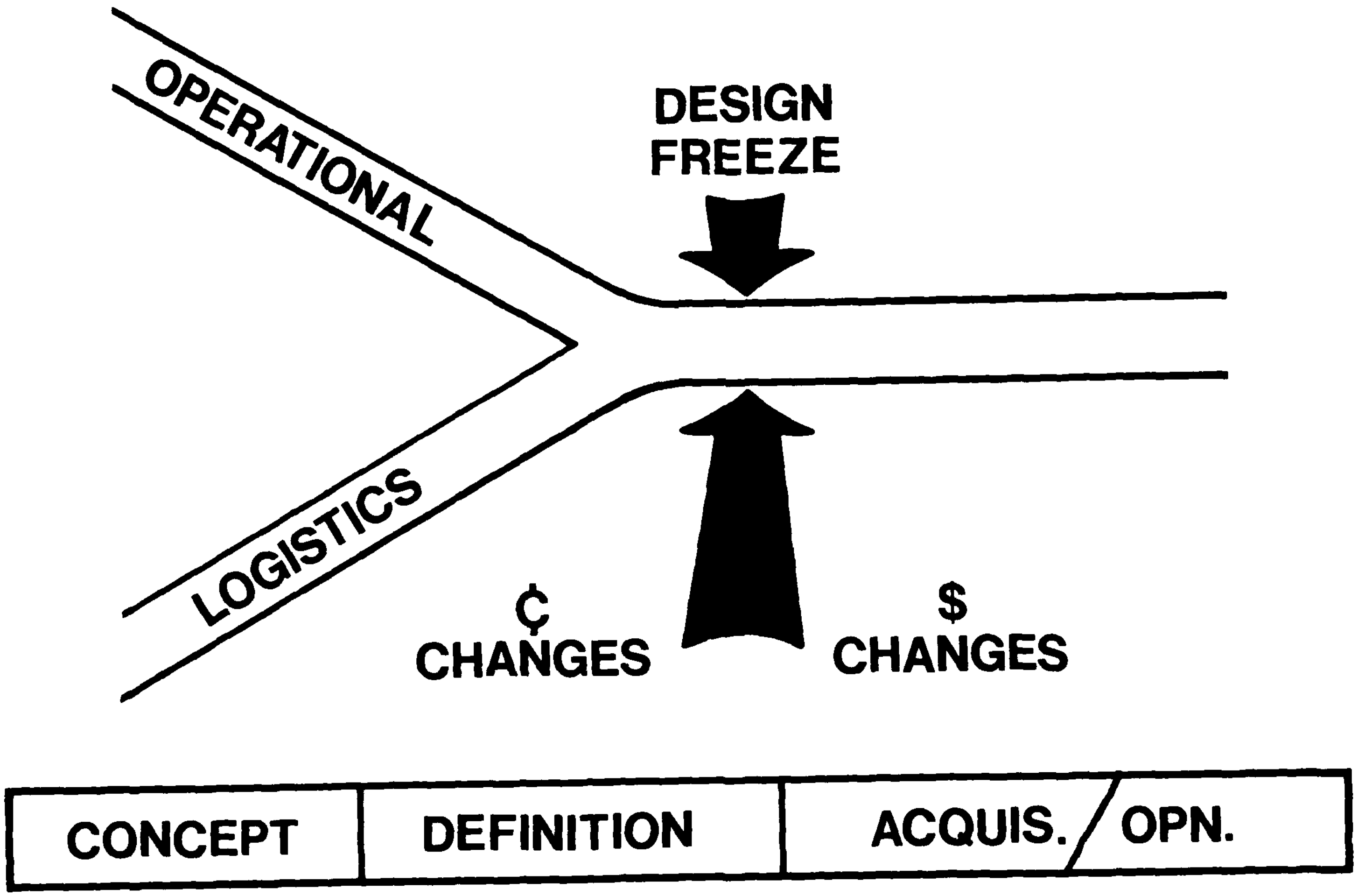
The concept of Integrated Logistics Support is that support requirements are included in the initial and all subsequent design trade-offs. With regard to support the following are design objectives:

1. Eliminate support requirements when practical
2. Reduce remaining support costs to a minimum consistent with.
   a. Operational readiness
   b. Technical performance requirements

The impact of logistics on systems design is shown in Figure I.J.1. As the operational aspects of design are successively more nearly defined the logistics characteristics can be described with increasing accuracy. changes can be made with little cost in the concept phase and with moderate Cost in the definition phase. Once the design is frozen both operational and logistics characteristics are fixed and any changes made are accomplished at significant cost.

Figure I.J.1.

Logistics Impact On Systems Design



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Section I.K.

Life-Cycle Costing, by Malcolm L. Ritchie

The basic notion of life-cycle costing is to reduce all variables of support required to a common basis of cost over service life of the hardware. "In the words of one of our contractor respondents "Everybody understands the money problem." "If you can get everything to this basis you solve many communication problems." It was also his view that the increased use of life-cycle costing would force the use of more trade studies in design.

Section II.

Direct Factors Influencing Design

Engineers do what they do because of what they know how to do, what they are instructed to do, and what they interpret to be the most rewarding thing to do. These are the basic notions involved in the direct factors influencing design, and are the basis for the efforts conducted to date in this area.

Section II.A.

Individual Cognitive Styles: Influence on the Design Process, by George Hankins.

There is a large body of literature describing personality types and behavior tendencies. As an example, a group at the University of Florida has investigated evidence that an individual's personality is related to his learning traits and his preferences for various instructional strategies (Smith, et.al., 1973). The findings of this study do indeed illustrate the wide variety of personality types in a typical engineering classroom. For example, 36% of the sample of students were Sensing-Thinking types (as defined by the Myers-Briggs Type Indicator), 64% were Introverted types while 57% were Sensing types (the M-BTI reflects 16 various personality type combinations of four pairs of preferences). The following, quoted from the summary of the study, indicates the significant differences observed as well as the subtleties of the tendencies:

> "Simple correlation data showed that Intuition (N) was associated with a preference for self-paced instruction to group-paced instruction, a view of self-paced instruction as being humanistic in nature and a claim that the best work in college courses is done where the individual can work by himself. ....Or to state it differently, Sensing (S) was associated with a preference for group paced instruction, a view of self-paced instruction as being dehumanizing and impersonal, and a claim that the best work in college courses can be done working with others."

The study concludes,

> "The above findings have shown that personality traits influence both student attitude and performance. ....A major weakness in college teaching appears to lie in the teacher's and the student's lack of recognition of each other's preferences and needs for different learning activities. The Intuitive-Thinking (NT) instructor, who likes to solve new problems and put things into a logical order, may not design very effective instruction for his Sensing-Feeling (SF) students, who dislike new problems unless there are standard ways to solve them, and who also value human likes and dislikes above logic."

The degree to which these varied types and preferences hinder or assist the learning of the design process is not yet clear. Communication between people of diverse personalities is a normal part of most human endeavor and much of the individual variation is no doubt tolerable. The results of this and other similar studies, however, appear to be of little practical significance in an investigation of factors influencing the design process. What is needed is a unifying concept

which will define a manageable number (hopefully two or three) of individual traits which may be evaluated for their relationship to design techniques and styles.

The manner in which designers learn, recall and utilize information can be expected to influence design decisions and strategies. Studies by Gordon Pask and B.C.E. Scott at Systems Research Ltd. in Richmond Hill, U. K. have investigated areas of adaptive learning which related individual cognitive styles and ability to recall and utilize data (Pask and Scott, 1972).

These studies sought to identify patterns in human learning. A brief review of the nature of their experiments will illustrate their approach. Two imaginary taxonomies of "Martian Fauna", Clobbits and Gandlemullers were constructed. Information on ten sub-species of Clobbits was broken down into five categories and written on a series of cards. These cards were arranged, face downward, in rows which corresponded to different classes of information. One vertical row contained, for example, drawings of each of the ten Clobbits and other vertical rows gave information on a particular aspect of the species such as habitat, physical characteristics, etc.

Subjects were introduced to the task goal (learning the taxonomy) and informed of the arrangement of the cards. The experimenter observed the order in which each turned up the cards, replied to any questions (provided the reason was stated for asking them) and recorded any notes (new cards) generated by the subject during learning.

On the basis of their behavior during this activity subjects could be divided rather unambiguously into two groups. There were the serialists, or step by step learners, and the holists, or global learners. The serialists formed rather simple hypotheses as they moved from card to card, whereas the holists, who made more complex hypotheses, tested these by moving among the cards in a different manner.

The serialists utilized string-like cognitive structure related by simple data links. They tended to divide problems into linked sets and showed a preference to be certain of one step before proceeding to the next. Holists, on the other hand, employed more complex individualized linkages and tended to assimilate broadly in personalized patterns.

Having observed the different orders in which serialists and holists turned up the Clobbit cards, Pask and Scott could then construct linear instructional programs which corresponded to these strategies. This they did for a second taxonomy, that of the Gandlemullers. The two linear programs thus constructed were equivalent in that each provided a complete description of the taxonomy, but different in the concepts they instructed and in their structure.

Since subjects had already been classified as either serialists or holists the Gandlemuller programs could be used in either a matched or a mismatched fashion. A matched sample was made up of both holist subjects given the holist program and serialist subjects given serialist program. The

mismatched sample also contained two learner/Program Groups, holist/serialist and serialist/holist. In all cases subjects had to complete each frame successfully before moving to the next and they were required to repeat the entire program until they completed an error free run. A 30-item test was then administered which was aimed at determining both factual knowledge (4/5) and ability to generalize (1/5). The test results were unequivocal. All members of the matched groups scored between 28-30, whereas scores for mismatched students fell between 7-21 with an average of 14. The argument for matching instructional materials to learning strategies could hardly be clearer.

Tc make the parallels clearer mention should be made of a distinction which Pask and Scott were led to draw within the holist group. This is a distinction between irredundant and redundant holists. Both sub-groups image an entire area of knowledge, but whereas the irredundant holist's image contains only relevant and necessary components, that of the redundant holist is embedded in a network of redundant information. This information, although logically irrelevant, is of vital psychological importance to the individual. (The linear program used in the experimental study was written in redundant holist style although holist subjects of both categories were used).

The results seem to indicate that the quality and durability of learning (the reduction of uncertainty) are critically dependent upon a match in natural cognitive strategies and instructional material. Such distinctions in individual cognitive strategies may be reflected in the design process. It seems reasonable to consider two further questions: (1)are design procedures influenced by the form or format of the material available to the designer, i.e., are designers more likely to use data or information in a format suited to their cognitive style than mismatched data, and (2) are there classes of design strategies which correspond to serialist or holist cognitive strategies?

References

1. Smith, Irey and McCaulley, "Self-Paced Instruction and College Student Personalities," Engineering Education, Vol. 63, No. 6, Mar. 1973.

2. Pask, G. and Scott, B.C.E., "Learning Strategies and Individual Competence", Int. J. Man-Machine Studies, Vol. 4, p. 217, 1972.

Section II.B.

Work Statement, by Malcolm L. Ritchie

Probably the most important single thing which governs the design process is the statement of what is to be achieved. In Air Force contracting procedures, this is the statement of work and it is accompanied by a list of specifications. In other cases it may be described as a written statememt of the objectives of the design. In either event the statement or design objectives is the task description which the engineer uses to guide the design process. It is the formal statement of what he is trying to achieve. It will usually be written in terms of a functional problem which the equipment is to solve, although it may be written in the form of a particular machine or product which will have a given set of characteristics. The work statement may be a simple statement which can be written down on one page, or it may have many pages and refer to a number of subsidiary documents, each of which may be of some length. These subsidiary documents are called specifications.

Meister, Askren, et. al. (1969) reported in a study of the use of human resources data that the way to ensure that human resources data would be employed in the design would be to have appropriate criteria included in the work statement. This is an implicit indication of the extreme importance of the work statement and the primary task description of what is to be designed and the primary reference for the evaluation of a design against its intended purpose. The work statement for a military contract is the primary reference against which the contractor will be evaluated for performance of contract task. It is difficult to over estimate the importance of the statement of work and its subsidiary documents.

One difficulty with regard to study of the work statement is that the work statement will develop over the design cycle and may become quite complex. In practice the design objectives will be general to begin with and as the system program office (SPO) and the contractor work with each other there will begin to be a more specific statement about what is being designed and what the characteristics will be. The work statement development would be extended to include more and more specific details, and the specifications that are to be applied will also undergo a history of transition from general statements to begin with to more specific statements of system desicription and applicable specifications.

The statement of work and referenced specifications are the logical and most obvious beginning place to influence the engineering design process and indeed over the years there has been a significant effort aimed at producing the kind of handbook which could be present in the design process and which can be called out as being an adequate guide to design for human resources implications. At first glance it appears that this approach works on the problem at precisely the correct point. In practice over the years, however, this approach to the system has not

had as much affect as would be desired. The general summary is that human resources data have simply not been incorporated into the design processes to the extent they should have been. A part of the reason for the present effort is due to this short coming and the present research intends (1) to discover why the situation has not worked better (2) to explore better ways of impacting the design process.

The SPO has difficulty in calling out procedures, design objectives or criteria for test or evaluation in the human resources area which can be quantified and identified at the point of design. Because of the requirements for military control of equipment once it has been acquired, the procedure for evaluating whether the design has been successful is a series of tests which are executed at the time of delivery. If the equipment passes these tests the contractors are paid, the equipment delivered and whatever problems are inherent become the property of the Government. This being the case, the SPO needs to be able to tell the contractor through the work statement and specifications exactly what is required, then be able to recognize in the delivered product that the work statement has indeed been accomplished and the design meets the existing criteria.

This poses a considerable problem. It is not immediately obvious in the physical appearance or operational tests just how many man hours will be required to maintain the equipment. It may be a bit more obvious how many operators are required but the maintenance manhours and skill levels required are much harder to quantify. The maintenance costs may be a large portion of the total cost of the hardware and such costs are scattered over the life of the equipment. The SPO sometimes has a companion problem. They can be in the position of knowing how to reduce maintenance costs with somewhat higher design and procurement costs. However, they may be unable to acquire the additional immediate funds required to lower the total cost over the life of the equipment.

Another problem involved in the impact of the work statement may be illuminated from the discussion with an electro-mechanical equipment manufacturer who makes subsystems for both military and airline customers. He notes some significant effects of the different methods with which they could do business with the two customers. The manufacturer indicated that the military customer maintains an adversary relation with the contractor. The customer writes all the specifications and regulations before contacting the contractor. It specifies design and test criteria and renders final payment when the equipment is delivered and tested. It either does maintenance itself or writes separate contracts for maintenance. The manufacturer, therefore, has relatively slow and inaccurate feedback on the service experience of the equipment. Frequently, problems come to the manufacturer long after they've been encountered in service. Failed equipment examined after this lengthy interval frequently defies analysis as a result of additional damage through rough handling of the equipment during the period.

This manufacturer deals with the airline customer in a quite different

way. The airline customer sits down with the contractor before the equipment is defined. They negotiate appreciable specifications and regulations. In recent years the contractor has been writing maintenance-free contracts with the airlines. These are contracts to provide working equipment over a period of years (typically 5). If any equipment malfunctions during that period it is removed and replaced with a serviced piece of equipment at the location of the contractor. In this mode of operation the maker gets the equipment back as soon as it fails. The feedback is fast and accurate. With feedback information of this quality coupled with financial incentive, redesign and production modification is quite rapid.

To what extent may the rapid feedback and financial incentive be employed within the procurement methods government uses? They seem to be separate variables which may be untied from other aspects of contracting so the military systems can be reworked to achieve these objectives without compromising the advantages to the Government of the way it does business.

Another point in this examination of the statement of work is in the example of the F-5 airplane. This craft was originally built by Northrup, as a company venture. The characteristics of the aircraft were such that it came off the line at lower cost than other aircraft which were designed at the same time through the standard military procedures. It had exceedingly high performance for the size, weight and cost of the aircraft.

A look at the procedures used in design of the F-5 is revealing. The company had absolute control of the work statement and the specifications that went into the design procedures. The design group was able to trade off various aspects of the objectives in the work statement and to trade off various aspects of the specifications as a part of the design procedure. They were able within a reasonable period of time to wind up with low cost, high performance and light weight. These admirable objectives appear to have been achieved within a reasonable period of time because of the ability to enter design objectives and specifications into their design trade-studies.

Section II.C.

The Base for Trade Study Analysis, by Francis J. Jankowski

As a base from which to start an investigation of trade studies, certain assumptions were made concerning the history and nature of trade studies.

Figure II.C.1. shows some of the individuals or organizations who may be directly involved in a trade study.

Figure II.C.2. shows time history of a trade study. The possibility of interactions beyond that particular study and feed-back in the process are important factors. The final evaluation, item 5, may not be performed (at least, not formally).

Trade studies may be performed at various levels, which will influence the effort, the techniques and the reporting. Two approaches to categorization of levels are given in Table II.C.1.

A and B in the table are two separate but corresponding organizational structures for categorizing trade studies. Organization A puts emphasis on size of project, and B places emphasis on interactions, but the two are very much related and overlapping.

Literature Search. A preliminary search was made of cataloged texts in the library and of reports known to the investigators. The literature search is continuing.

An initial conclusion is that there is very little literature on trade studies as a tool of engineering design. The most extensive coverage is in A Methodology for Systems Engineering by Arthur D. Hall, Van Nostrand, (1962). This text gives five references to trade-off relations in its index. The discussion on value systems is particularly good, with eleven steps proposed for value system design.

Other texts make reference to trade studies, referring to the difficulty of value assignment, and the subjective nature of the process. None contain extensive discussions or recommendations on procedures.

The search of journals and reports uncovered much literature on decision theory and related topics, but no references directly relating to trade studies. The search of the literature for information on decision theory and related topics, and an evaluation of how these subjects might be applied to engineering design is continuing.

A second conclusion is that case studies involving trade studies are not reported unless the trade study was either required by contract, statement of work, or by some other directive, or the trade study was a reason for or central part of the work being reported.

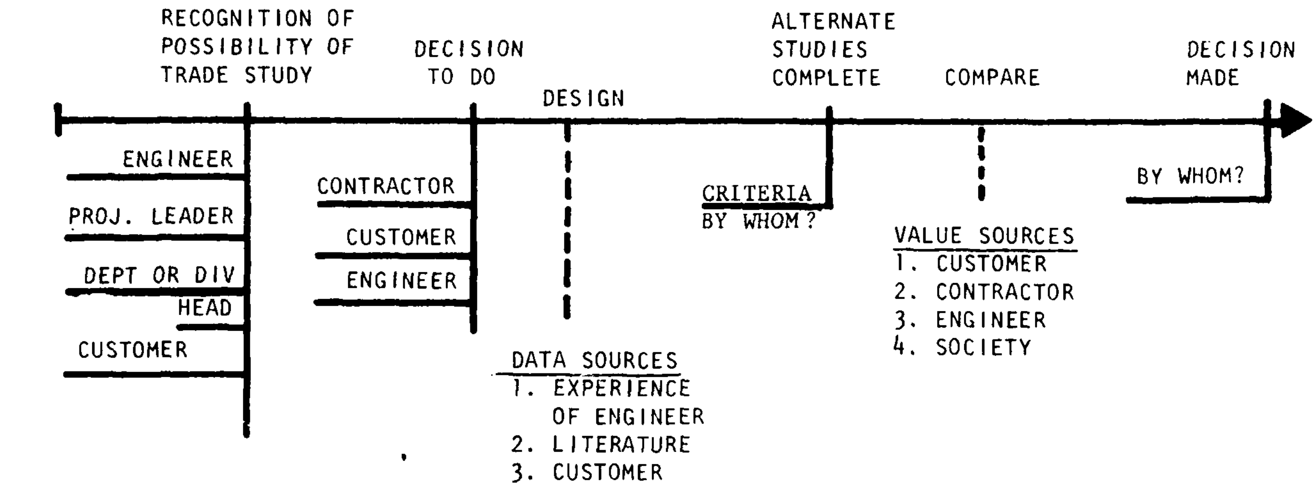


FIGURE II.C.1.

Individuals or Organizations Who May be Involved in A Trade Study

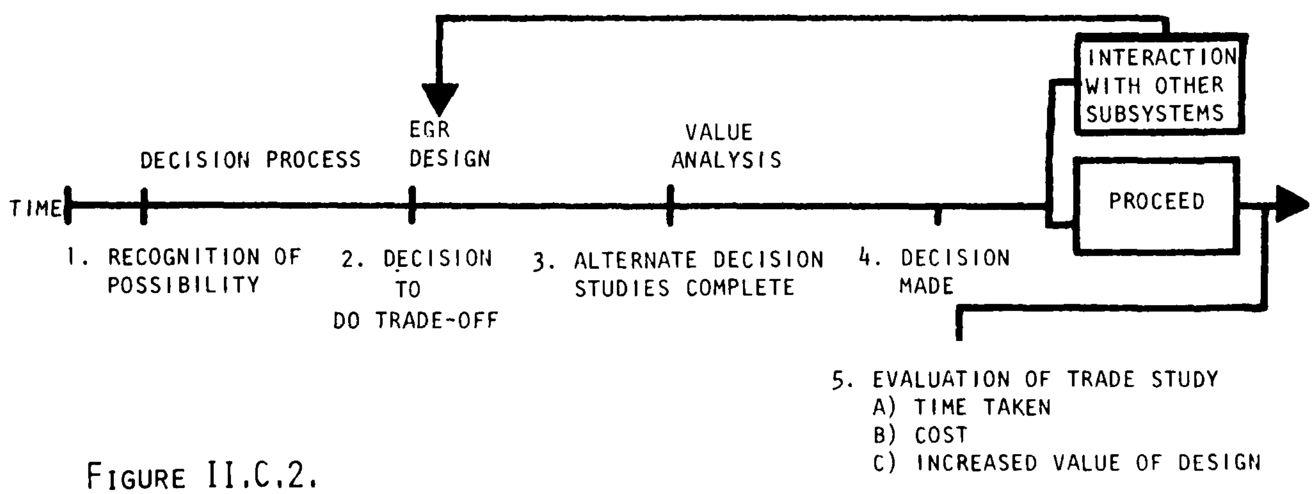


FIGURE II.C.2.

Time History of A Trade Study

TABLE II.C.1.

LEVELS AT WHICH TRADE STUDIES

ARE PERFORMED

A*	B
1. Policy Analysis	1. Value vs.cost vs.other methods (entirely different system or approach to reach same objective).
2. Force Structure Composition Studies	
3. Weapon System Selection Studies	
4. System Optimization Studies	2. Trade between parts of subsystems or between subsystems, evaluation of interactions important.
5. Subsystem and Detail Design	3. Entirely separate alternatives with no or minimal interactions with other subsystems.

*Suggested by Dr. Gordon Eckstrand, Human Resources Laboratory, Wright-Patterson AFB, Ohio.

NASA, ASEE, and NSF have separately or jointly sponsored a number of projects which directly involve and report on trade studies. Two of the more interesting ones are:

ICARUS (MIT Press, 1968)
SAINT (Stanford University, 1967)

The first purpose of these projects is to train engineers, scientists, faculty, and/or students in systems engineering; trade-offs and evaluation of alternative approaches are most important. A second purpose is to develop ideas and proposals which the sponsoring organizations might find useful as a source of ideas for new projects or for solutions to current problems. Each of the two projects listed above describes in some detail a half dozen or more trade studies.

Interviews. An important source of information and ideas are conversations with individuals who direct projects and/or supervise work where trade studies are done. Individuals interviewed to date are:

Propulsion and Power Office, ASD, Wright-Patterson AFB, Ohio
Ed Koepnick, Technical Director
Charles Cullom
George Letton
Fred Ehersbach
ASD, Wright-Patterson AFB, Ohio
Fred Rall, Chief Engineer
ASD/XR, Wright-Patterson AFB, Ohio
John Chuprun

Franklin Kelly
McDonnel-Douglas, St. Louis, Missouri
Jerry Whalen

Further interviews are planned.

Case Studies. The case studies investigated for data on trade studies have been limited to NASA, ASEE, and/or NSF sponsored design projects such as the ICARUS and SAINT projects mentioned above. Reports from the Case Study Center at Stanford University, from the auto industry and others are being studied for further data. Information is being obtained on availability of Air Force project reports for further case study analyses.

Analysis of Trade Studies

Trade studies, also referred to as trade-offs, are applied practically every time a decision is made, whether technical, economic, social, or other area. However, in engineering design, trade studies have been applied at a level where they are recognized only since the advent of the digital computer, which permitted analysis of large scale systems and pursuing of alternate designs without incurring unreasonable costs or unacceptable time delays.

Trade studies in the engineering design process have merely evolved. They are applied intuitively and subjectively. The techniques are rarely taught in engineering school and are rarely the subject of a scholarly publication or paper.

This study is directed toward a better understanding and utilization of trade studies.

Objectives. The first objective of this study is to arrive at a better knowledge of trade studies: are there identifiable techniques; how, when, and where can they be applied; can they be required in a project. Any such knowledge gained can be passed on to Air Force engineers, contractors, and engineering schools. The ultimate result would be improved designs and improved products delivered to the Air Force.

A second objective is to obtain further knowledge on how trade studies might be effectively used as a vehicle for introducing and utilizing human resource data (HRD) in engineering design. That trade studies can be used for this purpose has been demonstrated in the work of Lintz, Askren, and Lott.[1]

In addition, engineers are a human resource and if their work can be made more effective by these studies, a further objective will be served.

Investigations. A three-pronged attack on the subject of trade studies was initiated.

1. Literature search
    a. trade study cases
    b. trade study procedures and related topics
2. Experiences and opinions of experts
3. Evaluation and observation of actual case studies

A fourth approach, the initiating of experiments in the application of trade studies, will be undertaken after results from the first three approaches are evaluated.

Reference

1. Lintz, Larry M., Askren, William B., and Lott, Wayne J., "System Design Trade Study: Engineering Process and Use of Human Resources Data," AFHRL-TR-71-24, June 1971.

Trade Study Discussion and Conclusions

Nature of the Design Process. One statement made by all individuals interviewed was that engineering design is the performing of trade studies. Design and trade studies are the same operation. Trade studies done at the lowest level (see table of categories of levels) often are not recognized or labelled as trade studies, and formal procedures are rarely applied.

The phases (or stages) through which a project passes are shown below in Figure II.C.3.

The progress of a typical project is shown in the next diagram (this method of describing the course of a design was suggested by Ed Koepnick, Propulsion and Power Office, ASD), Figure II.C.4.

This figure shows a design as oscillating within an envelope. As the design proceeds, it will look good at times, and other times encounter problems. A trade-off in one area could affect another; a subassembly may not meet specs, or may perform better than required, etc. As the design proceeds, the oscillations become smaller as the design becomes refined and more firm. At times there will be perturbations in the entire design (in the envelope) which might be due to a change in specs, the unavailability of desired materials, etc.

This analysis of the design progress suggests that trade studies can have a larger and more obvious effect during the concept phase, but can be important throughout the life of the project.

Timing. Accepting the postulate that trade studies and engineering design are synonymous, it must be concluded that trade studies are useful and desirable throughout the life of the project, from concept phase into the operating phase and possibly into the deactivation phase.

A frequent comment was that cost was not given enough importance in early phases of a project. This may be corrected by the design-to-cost approach.

Initiation. At the lowest level, trade studies often are performed informally, possibly even subconsciously. For larger or more important problems at the lowest level, and for problems at other levels, trade studies may be initiated in various ways:

1. They may be required by contract or other directive.
2. It may be the personal choice of the design engineer.

3. It may be undertaken because of a deficiency in design (specs not being met).
4. It may be initiated because of a dissatisfaction on someone's part on cost, performance, or other factor.

There is a concern that requiring trade studies could lead to perfunctory studies which would be weighted to reinforce the original design; it could lead to more rigid stance by the designer and less rather than more complete consideration of alternatives.

Whether the above concern is real, or serious, is not known, but appears possible. Two approaches to countering this effect are:

1. Educating engineers so that trade studies will be one of their standard design tools which they will choose to use when it is advantageous to do so.
2. Require trade studies, and have an indoctrination plan to train and to obtain the acceptance of the design personnel.

Purpose of Trade Studies. The purpose of a trade study should be to produce the best design and best product possible within the constraints. It should be used as a design tool.

From both the published case studies and from opinions expressed by interviewees, it appears that trade studies frequently are used to prove or to justify a preconceived design. This may not be entirely bad in that it forces the designer to analyze his work more completely. However, it is not the most effective use of trade studies.

Methods. Uniform formal procedures for performing trade studies have not been developed. Making a trade study and reaching a decision requires selection of criteria, assigning values and/or weighting factors, and seleching a basis for the decision. An evaluation of the sensitivity of the decision to variations in the values or criteria is also of value. These processes require many subjective judgments on the part of the design engineer and others having responsibility for the decision.

Values are often transformed into common units, such as cost, performance, or weight. Subjective judgments or consensus of groups are needed for these transformations.

Trade studies may be made with a reference design, or a base design, to which alternatives are compared, or the trade studies may be done by initially considering all alternatives likely. McDonnel-Douglas engineers commonly use a base design. The engineers responsible for the ICARUS and SAINT designs considered all alternatives equally. It appears that other factors have a stronger influence on the success of trade studies than the presence or absence of a reference design. In the cases observed, there was no noticable effect of having or not having a reference design.

Assigning values is a difficulty in applying trade studies. Trading off weight, performance, cost, schedule, complexity, reliability, maintainability, operator morale, and others, require developing equivalencies. Obtaining consensus and applying sensitivity analysis can be used to reach decisions.

A difficulty (or a defect) in the process can enter when the decision makers are not the same individuals who perform the analyses. The decision makers may not be aware of the assumptions, the method of value assignment, the uncertainties and the variability in values, and other factors which can be masked by the analysis and results.

A need was frequently expressed for data banks to aid in trade studies and in design. Data banks for engineering design, for human factors, and for life-cycle costs were mentioned.

Life-Cycle Cost. While life-cycle cost is a factor along with performance, acquisition cost, weight, etc., it was commented on often and at length in discussion of trade studies, putting it in a class justifying comment here.

Most individuals agreed that it is desirable to use life-cycle cost as a design factor. There was uncertainty among some as to the feasibility of using it, and occassionally a questioning of value to the design.

Problems associated with developing and using life-cycle costs are:

1. History and life of military equipment are probabilistic; they are not predictable as, e.g., equipment used by airlines.
2. Contractors, bidders, and advocates of particular designs are likely to choose values and analysis methods to make their design appear superior. Life-cycle cost predictions may not be realistic.
3. Operation decisions are likely to have a greater impact on life-cycle costs than design decisions.
4. Design changes to reduce life-cycle costs may not result in savings in the near future since the military is organized for current needs, and these costs will not change as rapidly as the need for the services.

Decision Theory. A review of decision theory has been undertaken. Much of decision theory has developed to aid in making operational decisions, economic decisions and decisions in areas other than engineering design. These approaches will be evaluated for application to engineering design.

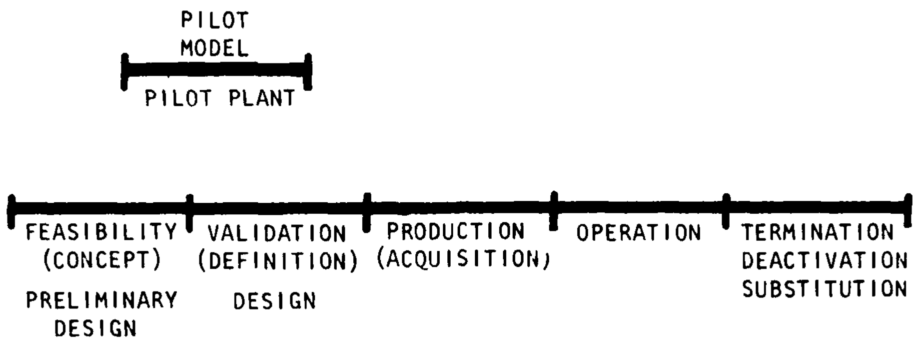
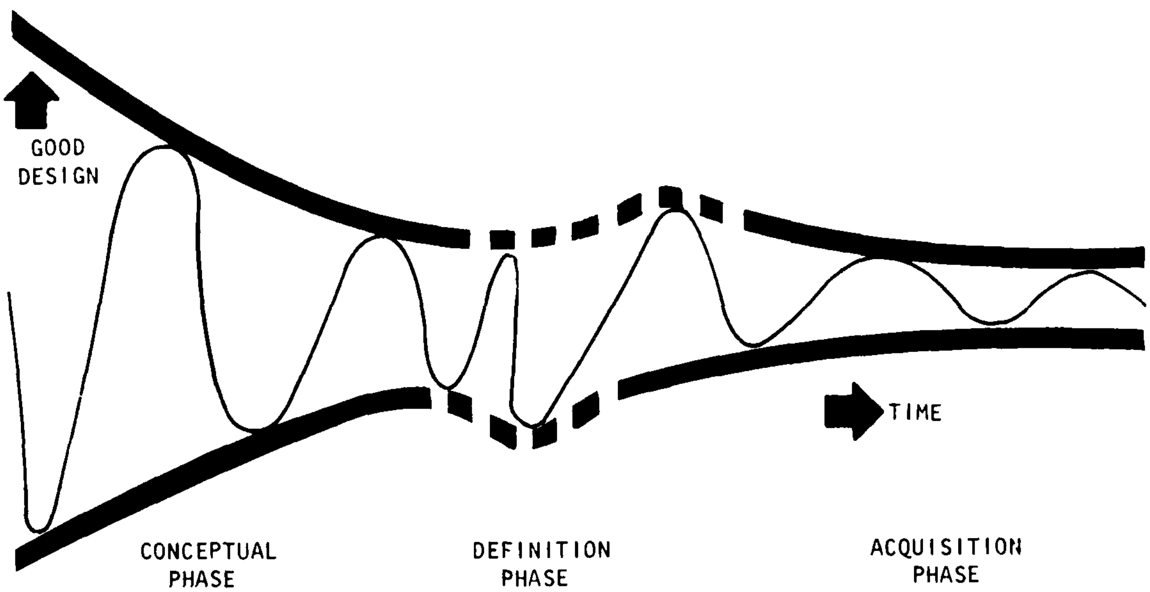


FIGURE II.C.3.

Project Phases



E. KOEPNICK

FIGURE II.C.4.

Design Oscillation

Trade Study Research: Problems, Needs and Future Efforts

From the investigations of trade studies to date, certain factors and needs have emerged. The more important of these are:

1. Trade studies should be developed as a regular tool of the design engineer. This would require conferences and short courses for practicing engineers, and the influencing of educational process for informing new engineers.
2. Identify and define methods of performing trade studies. Value assignment and decision theory are parts of this.
3. Developing creativity. A sufficient number of quality alternatives are needed to make trade studies effective. Committees, consultants, and other approaches may be used for more important problems.
4. Get the design engineer to cross lines:
   (a) to cross into areas other than in which he was trained or is currently working.
   (b) cross into design areas other than that to which he is assigned, to communicate and interact with designers on other phases of the project.

Section II.D.

Perceived Reward Structure, by Malcolm L. Ritchie

The formal method of laying out the objectives for a given design effort are in the statement of work specifications or are in the written statement of design objectives. There is another set of influences which act in a reasonably direct manner upon the output of design. This set of influences includes the individual designer's perceptions of what behavior on his part will be rewarded by his company and his superiors. They (Perceived Reward Structure) may be explicit or implicit. In either case they are undoubtedly very real and very important influences on his behavior.

When a design engineer is at work in a given setting he is aware that a certain pattern of behavior on his part will be rewarded by promotions, advancements or assignment of desirable jobs and projects. The most important single determiner of his advancement and his progress in the company is his relation with his immediate superior. It is this superior who will likely determine whether the design engineer is promoted, gets a pay raise, or gets advantageous assignments. Therefore, the engineer pays a good deal of attention to the formal instructions which are given him by his superior. He also pays a good bit of attention to attitudes and past behavior of that manager in order to make a prediction of what behavior on his part will be rewarded. Ordinarily it will be true that the designer can expect his manager's attitude to be congruent with written statements of objectives. Sometimes, however, these two things might be different. His manager may express some personal preferences for various characteristics of design which are not written in any of the specifications or the designer may remember preferences on the part of his manager which he learned from previous experience. It is quite possible for these implicit preferences or stated verbal objectives to be at variance with the formal statement. In this case the designer is in a conflict situation which can be very difficult for him to handle. An experienced designer will learn fairly quickly to pay a great deal of attention to the preferences of his manager even though they may be seldom expressed and even sometimes only hinted at or only observed through long years of observation. Regardless of the degree of explicitness or regardless of the awareness of the manager of his own design preferences, the working design engineer who perceives that these preferences do exist finds that he must pay attention to them. He therefore works dilligently in order to make sure that the manager is pleased by his output as a designer.

It is probably true that the design process cannot be understood without a knowledge of the management reward behavior on the designers. This may be especially true of human resources concerns. Managing engineers may seldom have had a great deal of exposure to human resources designs variables, but they can be expected to have long years of exposure with mechanical and physical design characteristics. Therefore, their attitudes and unconscious biases against design features are based on human resources variables in favor of those based on physical variables.

To choose a hypothetical illustration we may lift an advertising slogan from an aircraft company which states that they have a reputation for "flying farther and faster with a greater payload." Let us suppose that given manager has these principles implicit in his design approach. Notice that these three criteria of performance have no statements in them with human resources implication. There is no statement here of reliability of maintainability, or reduction in the number of operators. Let us presume that a manager has adopted these principles as his guide and now confronts a design decision in which there is some attenuation of these three objectives in order to enhance maintainability or reduce the required number of operators. If the manager is aware that he favors these three performance objectives, then it may be possible for the designer to explain in the trade study that sacrifice at a certain point is in order to obtain lower overall operation cost through better maintainability. For example, if this same situation were approached and the manager was unaware of the degree to which these three performance variables were implicit in his criteria for evaluation, the designer may have a more difficult problem. In this case he may feel that it is useless to try to argue the manager out of his position but what he needs to do is come up with a design that will be approved.

It is like that this variable, perceived reward structure, is an important one to be studied with regard to influencing the overall design process. It is probably true also that the criteria used by engineering managers for evaluating designs has many implicit values, that is, the manager makes decisions on hunches, and preferences based on previous successful designs.

Section II. E.

Nature of the Design Group, by Malcolm L. Ritchie

The design process is influenced markedly by the experiences of the people who comprise the group and the structuring by which certain elements of that background become dominant. A design group must contain expertise in all the areas which are critical to the design. Ordinarily engineering managers exercise great care in assembling a group with the kind of background they think adequate for solving the given design problem. It is their estimate of requirement of a situation which causes a given mix of training, experience, background and orientation. This particular mix will then have an important bearing upon the nature of the products being designed.

The differences among groups will appear in every element of the design process. Even the perceived meaning of the work statement may differ. The same words may be interpreted differently by engineers of different experiences and backgrounds. If a group of people is to translate the words of the work statement into a design concept it makes a great deal of difference what the terms and concepts mean.

From the standpoint of human resources implications of design it is obvious that it makes a great deal of difference whether the design group includes someone who has a background in human resources variables and knowledge of the way design impacts upon these variables. Elsewhere in this report it is noted that one relatively new approach to the composition of a SPO is that of intergrated logistics support. A large part of the cost of a given weapon over its life cycle—is manpower costs including personnel knowledge about logistic support. The design process allows support variables to be traded off with other aspects in design. The design effort would clearly be different without this component.

There are two general approaches to incorporating a given kind of knowledge into a design group. The first approach is to make sure there is a specialist assigned to the design group for each special area which needs to be incorporated in the system. In this approach a team is formed by putting together specialists in all of the representive areas. The other approach is that of choosing design engineers who themselves have an understanding of the areas which are important in the design. The difference between the two approaches are subtle in some respects but some of the subtleties are important.

Ideally, if one could acquire an individual who was thoroughly competent in all the aspects of design which were relevant to the given design problem there would be a minimum of cross communication and interpretation and maximum efficiency. This is not necessarily realizable since it is probably true also that there needs to be at least two people in a design group in order to speed clarification even if there is no more information. On the other hand, if say five given areas of competence are required and one puts together five people, one from each of these given areas there may be a large amount of time taken up on communications and in trying to breakdown barriers that exist between the different areas. At times such problems have become insurmountable. Another mechanism which works in this process is that some individuals tend to become dominant in a social group and the background of the person who becomes dominant may become over-represented in the resulting design of the product.

It is probably true that there is a very fruitful area of study in this concern with the nature of the design group. The variables will include importantly how the mix of various specialties must be put together in the output product and how this mix relates to the availability of trained people. If for example, a product is electro-mechanical in nature it would be desirable if the group is made up of people who are electro-mechanical specialists. It seems clear that the product is likely to be more efficiently designed than if electrical engineers are put together with mechanical engineers. The difference is that they must learn how to trade off electrical and mechanical aspects in the design of the electro-mechanical products. In a similar way it would be desirable if human resources background were a part of the training of a number of engineers along with whatever machine specialities were required by the given design. If, for example, a control system is involved it is conceivable that control could be much more easily designed if done by a group of people who were competent in manual control and competent in electronic control who were put together to work out the control system to be operated by man. It is presumed that the system is likely to work better this way than if there were electronic control people and manual control people, neither of whom understand the tools and techniques of the other people in the design group.

One illustration of a way to work on this variable was given in the discussions of the B-1 program with regard to maintainability. The design engineer group was augmented in their understanding of maintainability requirements through the process of providing a group of old-line maintenance people to be on site and work hand in hand with the design engineers. The result was a good bit of discussion between the two which resulted in the design engineers learning more about maintainability problems and at the same time the maintenance people learned more about the real problems of design. The point being made here was that information about maintainability was augmented in the design process through the assignment of people to be on site to communicate maintainability considerations so they could be more realistically traded off in the design process.

Section III.

Formalized Approaches to the Design Process

There are several different approaches to design variables and design processes which may be described as formal approaches. By formal is meant a mathematical model, a logical outline or a similar structural approach to detecting and depicting the underlining variables which may be used for a description or all or a part of the overall design process.

Section III. A.

Decision Theory, by Malcolm L. Ritchie

In several areas of the study there were indications of decision processes which were important to the various aspects in which design was being described or analyzed. As a result of this an effort was made to become acquainted with the current status of decision theory. For this purpose, access was provided by the Air Force to a group of people from Decision and Design Incorporated who have been working for ARPA on decision theory. On the basis of information required, it is probably true that a good bit of utility can be obtained by carrying forward a study of decision theory in its relation to various aspects of design decisions and tradeoffs in the design process. A short summary will be given of decision theories as explained by Decision and Design Inc.

The elements of decision theory appear to begin with a decision tree as outlined in Figure III. A. 1. This decision shows the consequence of decisions as they would be traced out into alternatives and the results of various alternatives in the branches of the tree. This figure depicts a decision of a naval commander aboard ship to shoot or not shoot at an aircraft which has been sighted. For each of the two decisions, there are branching consequences which are determined by whether the aircraft was a friend or enemy. If the original decision had been to shoot, there are additional consequences which would be different for the friend and enemy depending upon whether the result of shooting was kill or not kill.

Each of these six consequences then is susceptable to having a value assigned to the total outcome. In this case the numbers assigned to values of the various outcomes are in terms of millions of dollars. The first item, the choice to shoot, it is a friend and there is a kill, shows the consequence to be assigned a value of -$9.5 million. This is the cost assigned to shooting down a friendly airplane and pilot. The next cost is the consequence of shooting a friend with no kill; this is assigned a value of -$3.5 million. The third consequerce is that of shooting an enemy aircraft when a kill results. For this case the value assigned is +$6 million. The fourth consequence, shooting down an enemy with no kill, was assigned a value of -$20 million. In this case there was cost of the action and the consequence of having a live enemy make a strike. The fifth consequence is that of a decision not to shoot when the aircraft turned out to be a friend. The value assigned is $0, which means no harm done, no actions taken, no cost borne. The sixth and final value is that of the decision not to shoot when it turns out to be an enemy. The consequences for this case were assigned the value of -$21.5 million.

Thus there has now been assigned a set of dollar figures expressing the consequences of each of the possible six alternatives of the decision of the commander to shoot or not to shoot. The values depend upon whether the aircraft turns out to be a friend or not a friend, is killed or not killed.

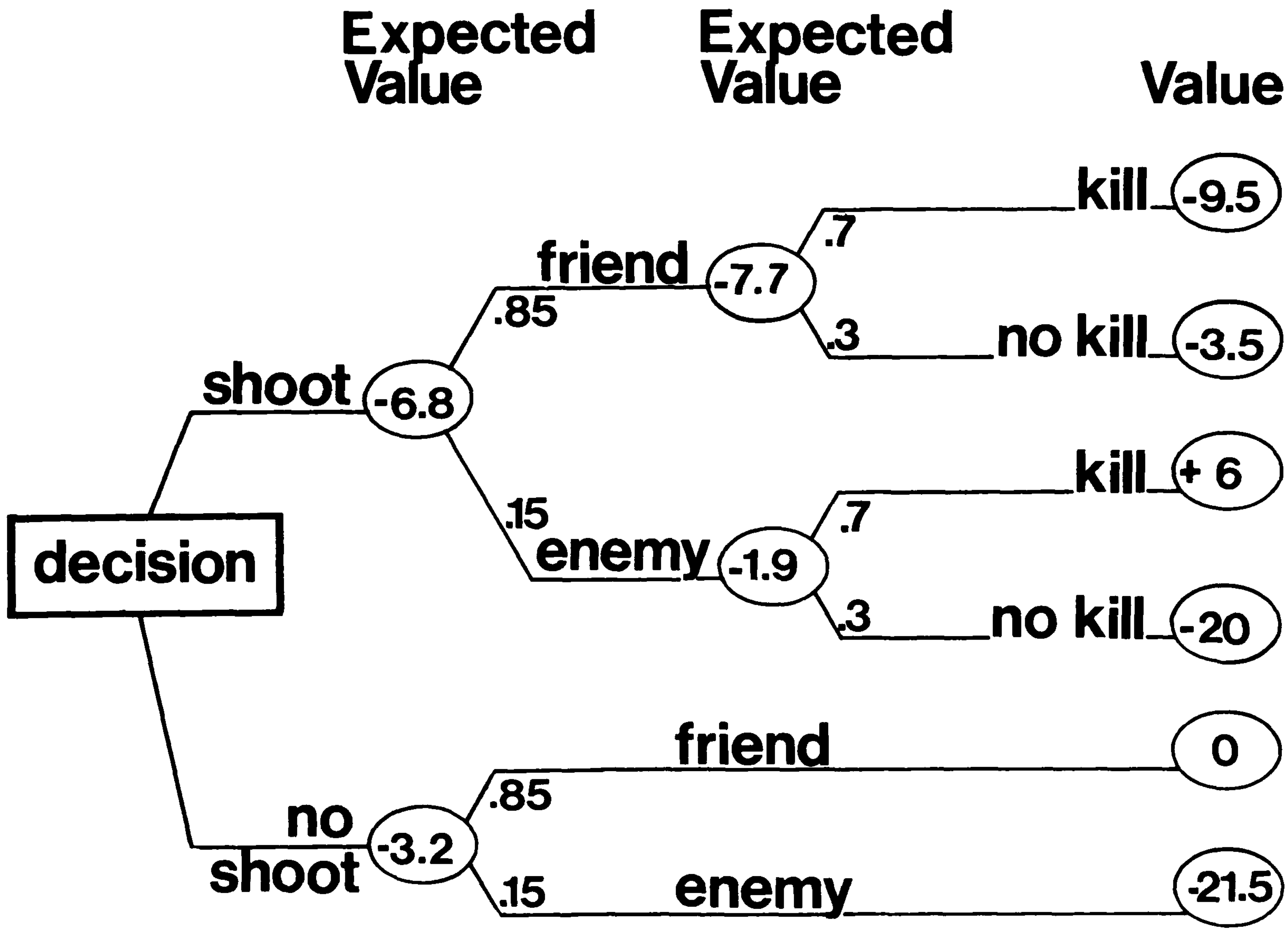


FIGURE III.A.1.

The next step in working out the decision process is that of assigning probabilities to each of the choice parts. The first probability was that of whether there would be a kill or no kill if the decision was made to shoot. This probability was calculated to be .7. There would be a kill if a shot was made and .3 probability remaining for no kill if no shot was made. The next probability assignment was that the aircraft sighted would be a friend or enemy. It was calculated through an estimate of the detection capabilities that there was a probability .85 that the aircraft which was sighted would be a friend, leaving the probability of .15 that it would be an enemy.

With these probabilities assigned it is now possible to work backwards towards a decision to get the relative values to be expected for each decision. Consider the top two consequences: that is to shoot and it turns out to be a friend, and the kill or no kill. The kill probability of .7 would be multiplied by the value of the consequence of killing a friend, -$.5 million. Combining this with the probability, .3, that there would be no kill times the value of -$3.5 million, results in a combined probability that the expected value of shooting a friend would be -$7.7 million. In a similar way the consequences of shooting an enemy could be calculated by combining the probability of .7 of the kill times +$6 million with .3 probability of a kill and -$20 million, to result in an expected value of shooting an enemy to be -$1.9 million.

In a similar way, the consequences of shooting at all can be determined by calculating the combined expected value of shooting a friend by the probability of its being a friend (.85), and the probability of shooting an enemy (.15) against the expected value of shooting an enemy (-$1.9 million). The combination of these probabilities of expected values results in -$6.8 million as being the expected value of the decision to shoot.

In a similar way, the decision not to shoot can be shown to have an expected value -$3.2 million when the 0 value of shooting a friend is multiplied by .85 and the -$21.5 million for shooting an enemy is multiplied by the .15 probability of its being an enemy. The combined expected value then of not shooting is -$3.2 million.

Through this calculation it can be shown then that the decision to shoot or not to shoot can be related to an expected value of -$6,8 million if the decision is made to shoot, against the -$3.2 million expected value if the decision is made not to shoot. Several points of interest appear here. One of the most obvious is that the commander who sights an aircraft coming toward him has two choices, and by both he loses. This is apparently characteristic of defensive action. Defensive action then is not calculated to result in great (+) values but instead is a matter of taking actions to minimize losses.

Another thing which appears from this method of calculating expected values would be the kind of change which can be obtained by changing the two sets of probability figures. The one set being the probability of a friend vs. the enemy, and the other set being the probability of kill. If additional cost could be expended to change the probabilities in either

case in a more favorable way, then the consequences for the original decision would need to be recalculated. We can calculate one such change in the expected value of the decision. If we presume that the defensive position of the ship commander can be changed by investing in equipment which would identify the aircraft appearing as friend or foe. Let us presume that this investment in IFF equipment changes the I.D. probability from .85 to .99. The consequences of this change in probability appears in Figure III.A.2. The differences in calculation between this and previous figures are shown as the different expected values for the decision to shoot or not to shoot. The altered probabilities change the expected values for shooting to -$7.6 million and the expected values of no shoot to -$.2 million.

The operational meaning for this change in IFF probability means that the commander decides not to shoot any time the IFF says it is a friend approaching. For the expected value of such a decision is -$.2 million against the -$7.6 million if he decides to shoot when the IFF says it is a friend. In this case with the high probability of the accuracy of the IFF he would be similarly ahead on the calculation to shoot only if the IFF didn't indicate it was a friend.

In this short discussion the basic aspects of the calculation of the expected value from a decision are shown. In addition, the illustration shows how changes in probability can be purchased by the application of information at one of the choice points and how these changes in probability can be related to the expected value itself.

Another point should be made clear even in a short course of decision theory. That is the difference between a good decision and a good outcome. It can be shown on the basis of the calculation that the expected value of a decision is based on probability statements. Even with a probability of .99 there is some possibility of the most unlikely outcome occuring; in which case there would be the tremendous - value of outcome experience. In this cas it still would have been a good decision because the probabilities would have been with that decision even though the outcome this time turned out to have been very expensive.

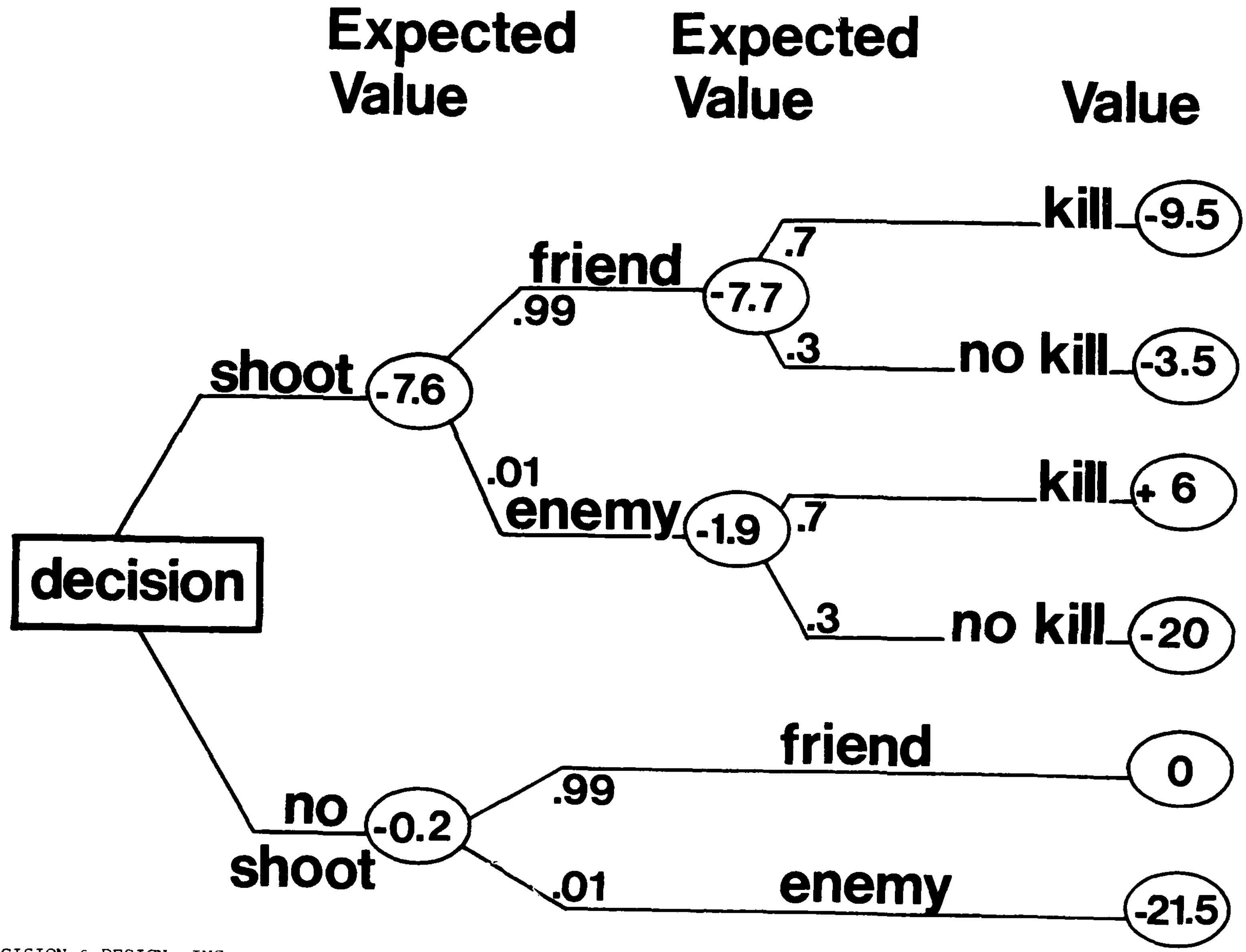


FIGURE III.A.2

Section III.B.

Design Synthesis, by Malcolm L. Ritchie

One interesting formal approach to the process of design is that called design synthesis by Ray Johnson, 1973 A, B, C and D. Design synthesis is based on optimization. It involves describing engineering design as a process of solving a system of equations. In Johnson's terms the rationalization of the design process amounts to transforming the variables in design tradeoffs into a set of simultaneous equations which may then be quantified for solutions.

Johnson points out that it is in the nature of the design process that it must be described by a set of simultaneous equations, whereas analysis can be described as solving a single equation. This difference is one way to describe why design is inherently much more complex than analysis. Analysis has a single equation and a single solution. Design has multiple simultaneous equations and multiple possible solutions.

According to the approach he calls design synthesis, design should proceed according to the following steps:

a) Make an initial formulation which includes the total context: that is, the object for optimization, the functional requirements, and the specific equations needed to allow optimization.

b) Work toward a final formulation which will be "normalized" in order to combine equations.

c) Make a variation study. The variation study will show how variables change as parameters change. It will be used to detect an overlap of domains.

d) Application to design. In this step a flow chart is constructed or a computation scheme is set up. Usually this consists of a complex set of equations.

e) Evaluation of design. In this step the equations are worked through to show what has been achieved and what sort of compatability there is with other designs.

In design synthesis, it is apparent that Johnson is constructing his model while thinking about design of relatively small components. In this case he can see his way through to making optimized solutions which may be fairly well described by the equations which he is working. If this same design approach were considered for a far more complex system, the results may be so tenuous that they would not approximate the apparent value which they would have in component design.

Section III. C.

Computer Manpower Models, by Malcolm L. Ritchie

In our study of formal approaches to design we considered manning procedures and the information that we could obtain there-from which might be helpful in identifying design variables. The U. S. Navy has considerable experience in setting up manning tables for ships. There is a restricted and determined set of equipment to be operated and a readily identifiable number of men assigned who must be carried aboard the ship. There has been an active effort in developing manning procedures but results have not been carried far enough to allow a ready identification of design variables for the equipment.

However, in this study, we ran across a summary of manpower models which are available to Navy personnel in studying requirements.

Figure III.C.1. shows a summary of the computer manpower models which are described in Hutchins and Prather, 1973. As shown in Figure III.C.1, they describe 101 computer manpower models which cover manpower requirements, active inventory maintenance, inventory projections, requirements and inventory analysis and projections, policy alternative generative models and productivity measurement models. For present purposes we have only described the existence of these models and have not studied them in detail.

FIGURE III.C.1.

Computer Manpower Models

model	stochastic	deter.	total
manpower requirements	10	13	23
active inv. maint.	1	19	20
inventory projection	9	10	19
req/inv. anal.+proj.		13	13
policy alternative gen.	1	10	11
productivity measurement	8	7	15

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Section III. D.

Duane Model of Reliability Growth, by Malcolm L. Ritchie

Among the interesting formal approaches which were uncovered in this study was one describing the improvement of reliability over the time that an item of equipment is in production. The formal statement of this principle is due to General Electric. The basic notion is that there are a set of influences which begin working on an item of equipment in production which, over a period of time, results in an increase in its reliability. The set of influences include the knowledge of failures, the feedback for the cause of failures, and the translation of this knowledge (a) into redesign of the equipment, and (b) into redesign of the production process. The effect is to eliminate, step by step, weakness in design or production which results in failures in the field.

The second basic variable in reliability growth is that the rate at which reliability grows depends upon the amount of effort which goes into the reliability process. Speeding up the process of detecting failures and feeding information gained back into the design processes will result in a steeper increase in reliability than would just a normal effort. There is a range for the rate of reliability growth which includes the notion that without a conscious effort reliability there will be some improvement which will occur. Some information will find its way back into the design and production processes. The other end of the range is that there will be some limit on how fast reliability can be improved even with the best effort that may be mounted. Some improvements can obviously be made, but there will still be some limitations on how effective the processes can be made even with the best efforts that may be mounted.

Section III.E.

Design Morphologies: Possibilities for a General Process Model, by George Hankins

As described elsewhere in this report the literature regarding design processes and methods is extensive and varied. Models of the process tend to alter according to discipline (design models for aerospace vehicles show significant differences from architectual design models) and even according to individual practitioners. There are several reasons why models of design may be expected to lack generality. Design, like creativity, is an individualistic, sometimes an idiosyncratic process. The hierarchy of intellectual abilities below (after Bloom's Taxonomy of Educational Objectives: Cognitive Domain) reflects the increasing levels of sophistication of design-related abilities:

<u>Intellectual Abilities</u>

1. Recall
   Memorizing concepts which can be recalled, stated or identified.

2. Manipulate
   To rearrange, reorganize or restate a concept or solve an equation.

3. Translate
   To change a message from one symbolic form (verbal, graphical, mathematical) to another form.

4. Interpret
   To recognize the significance of data, a concept or result.
   To draw inferences and compare answers.

5. Predict
   To predict results, trends, implications, consequences or effects.

6. Choose
   To independently select the appropriate concept required to solve a problem.

The higher levels (5 & 6) reflect those abilities that are the essence of design processes, abilities associated with experience and professional maturity.

The assortment of design processes described in the literature have some commonality along with their many variations and differences. Furthermore, the structures undergo modification with time. The model in Figure III.E.1.

illustrates a simple textbook example and in fact is a composite taken from several such sources. It is clear that many classic elements are included and equally clear that the true complexity of large-scale design is not reflected. Neither the maze of feedback loops nor the iterative nature of much of the activity is evident. For the most part, models reflected in the literature are inadequate for comprehensive study of the general process. Two avenues for further investigation suggest themselves: development of a family of models, each devised for a specific discipline (e.g., aerospace vehicles), or construction of dynamic model (such as J.W. Forrester's system dynamics) for investigation of critical interactions.

A distinction of significance in any morphology of design processes was a major item of discussion at the Design Activities International Conference 1973 in London (The Design Activity International Conference, 1973).

This conference was sponsored jointly by the Design Research Society in the U.K. and the Design Methods Group in the U.S.A. The attendees were principally architects, environmental planners, industrial designers and engineers. Some 105 papers were presented from 15 countries within the following major themes:

Design Morphologies
Design Processes Technique and Algorithms
Design Objectives
Design Case Studies
Design Education, Professionalism and Management.

There was an evident concern among architects (whose interest generally dominated the conference) for integrating consumer value judgments, evaluations and participation into the design process. Many papers investigated the desirability of utilizing user evaluation to influence the design process. However, few reported any effective actions to amass or evaluate such data from the users (public) and there were still fewer suggestions for techniques to integrate the results into the designers activities. The problems which they encounter appear to parallel in some respects the task of employing human factors data in the design process.

At the conference considerable discussion concerned the distinctions between simultaneous and sequential design morphologies (Figure III.E.2.)Sequential morphologies are process, or sometimes systems, oriented. Many engineering design problems fall into this category, frequently involving linear programming. These problems may be viewed as input-output mismatches requiring development of suitable transfer functions.

The simultaneous morphology, on the other hand, is an interactive process which begins as an ill-defined problem-solution couple with a more or less vague hypothesis of the problem and a vague idea of the solution as well. The task is to develop the problem-solution couple until an adequate and acceptable match exists. (In the case of design for production it is frequently desirable to accept the loosest fit that will work rather than the most highly refined design possible; this permits variations within the design as well as less expensive tolerances). This is best done by a continually developing dialogue between problem and solution, an interaction between the two. Many architectural designs are of this nature.

FIGURE III.E.1.

DESIGN PROCESS

I. ANALYSIS AND PLANNING

PROBLEM DEFINITION (OBJECTIVES)

IDENTIFICATION OF CONSTRAINTS

GENERATE POSSIBLE SOLUTIONS

II. PRELIMINARY DESIGN

SYNTHESIS AND MODELING

EVALUATION OF FIRST ORDER SOLUTIONS

SELECTION

III. DETAILED DESIGN AND TESTING

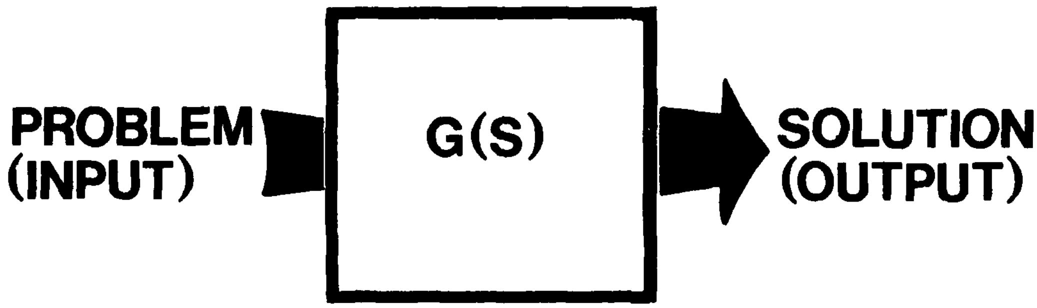
SUBSYSTEM AND COMPONENT DESCRIPTION

FINAL SPECIFICATIONS

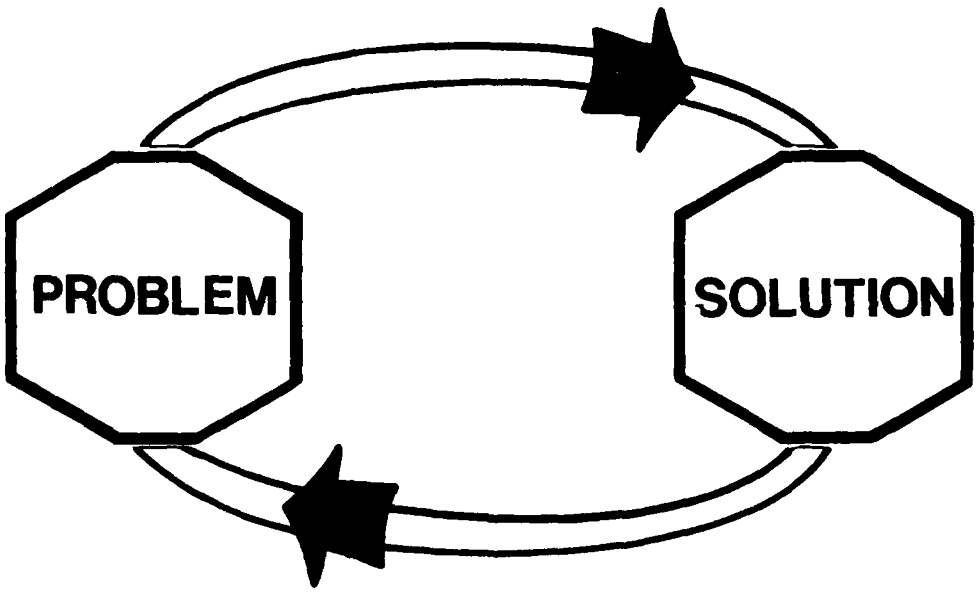
IMPLEMENTATION

FIGURE III.E.2.

DESIGN MORPHOLOGIES



SEQUENTIAL



SIMULTANEOUS

Sequential design frequently is applied to components or small-scale systems; the final specifications can be fixed with some degree of certainty early in the process. Many historical weapon system designs were, or were intended to be, sequential. Modern large-scale systems may be considered simultaneous morphologies, that is adjustment of goals (costs, performance, etc.) are required as the solution of the problem develops. This distinction appears to be important in consolidation of a general process model and is a factor in determining the feasibility of modeling the design activity.

References

1. Collected Papers, The Design Activity International Conference, August 1973, London.

2. Bloom, B., Taxonomy of Educational Objectives: Cognitive Domain, McKay, New York, 1963.

3. Forrester, J. W., World Dynamics, Wright Allen Press, Inc., Cambridge, Mass., 1971.

Section III.F.

Some Formal Approaches to Design Trade-offs, by Webster Wood

The engineering design process may be considered as the selection of components, methods, men and materials in order to accomplish a given goal or objective.

Optimal design, therefore, is that selection of components, methods, men and materials needed to "best" accomplish the stated goal.

Trade studies (or trade-offs) may be defined simply as that process whereby choices are made between alternatives.

Obviously, then, the engineering design process is, in essence, a series of trade studies, from the selection of the proper screw to hold two pieces of sheet metal together, to the selection of the proper engine to power a particular aircraft.

In order to obtain optimum design, a systematic methodology is needed to aid the design engineer in arriving at optimal decisions.

Such a methodology must take into consideration much that is subjective and/or judgemental in the design engineer's approach to problem solving, as well as attempting to attain a realistically objective and useful method upon which the engineers can base their decisions.

It was, thus, deemed that a review of the decision theory literature might be helpful in arriving at such a methodology to aid the design engineer.

The decision theory literature is quite voluminous and the review undertaken must, therefore, be cursory at best. However, certain techniques and methods repeatedly cropped up in the survey and these techniques were studied for their applicability to engineering design--from the point of view of the design engineer, that is, tentatively, the method should have the following characteristics:

1. It should be easily understandable by many different disciplines.
2. It must be easily adaptable to design problems.
3. It should be a method which can be used for small problems as well as large. That is, its use for small problems should not be precluded due to high cost or time-consuming manipulations.
4. It should present the information so that the arrived at solution is apparent to the engineer, his colleagues and to his superiors.

5. In all cases, it should aid in reaching an optimal solution.

6. If possible, it should include a numerical weighting system whereby the results of various possible alternatives may be compared directly and easily.

7. Above all, it should allow the full creativity inherent in the design process.

With the above tentative requirements as guidelines, the literature was searched for decision theory techniques which might be applicable, or which might be modified to be applicable, to engineering design decisions.

Those techniques most commonly referred to in the literature and apparently in general use were: PERT (Program Evaluation and Review Technique), Linear Programming (which includes Dynaic Programming and such techniques as the Simplex method), Monte Carlo, Delphi, and Decision Trees.

These five techniques or methods are shown in Table III.F.1, with the area in which they are most generally used, their form of input, analysis method, form of output, degree of difficulty and the probability of their application to engineering trade studies.

PERT, Program Evaluation and Review Technique, (Fishburn, 1964; Bellman, et.al., 1970; Moder & Phillips, 1970; Au & Stelson, 1969; Steiner, 1969; and Wagner, 1969) is a visual comparative, sequential technique used frequently in business and engineering management.

It is a time and activity chart used to visualize relatively complex programs, whereby each event is shown and the activity time for each event is given. Indications are given of the scheduling times for multiple tasks and a critical path method (CPM) is used to show which events or activities are likely to cause the most scheduling troubles so that these may be overcome before their occurrence. Computerization of PERT with (CPM) has become commonplace, especially where time and scheduling are of critical importance.

PERT is relatively simple to operate and easy to understand, but, for large, multi-task systems, may become somewhat cumbersome. Its applicability to engineering design without major modification is minimal.

MONTE CARLO (Fishburn, 1964; Hammersley and Handscomb, 1967; Wagner, 1969, and Gordon, 1969) is a technique that has been used successfully for solution of problems in business, marketing, distribution, traffic and nuclear systems, where random probabilities of events occurring are encountered. An analytical model of the real system is obtained using random numbers and a mathematical probability of the outcome is determined. Although computer programs are available and the degree of difficulty is thus minimized, very little in the way of random distributions occurs in the engineering design process, so that its use as an aid in engineering design is negligible in most cases.

LINEAR PROGRAMMING (Fishburn, 1964; Bellman, et.al., 1970; Moder and Phillips, 1970; Au and Stelson, 1969; Steiner, 1969; Dantzig, 1963; Bellman

and Dreyfus, 1962; Wagner, 1969; and Larichev, 1971) has been used chiefly in the business management field, including transportation programs, construction long range analysis planning, etc. Basically, it is a method whereby the problems are reduced to a system of linear equations which are then solved simultaneously. Obviously not too many real-life problems are perfectly linear, however most of them can be solved as linear systems without too much error. For those more non-linear systems, Dynamic programming may be used.

The output is an optimal solution, but the use as an aid in engineering design appears minimal to the design engineer himself. The degree of difficulty in setting up the system would preclude its use (economically at least) by the component or subsystem designer.

THE DELPHI TECHNIQUE or Delphi method (Brown and Helmer, 1964 and Dalkey, 1968), named for the Delphi oracle of Greek mythology, is basically what its name implies, i.e., "ask the expert". When decisions need to be made, or problems arise, questionnaires are set to a number of experts in the particular field, in an attempt to arrive at a concensus. Analysis of the answers and submission of a second questionnaire to the experts based on the answers is used to obtain a better, more firmly based concensus. However, it has been found that, in most cases, the initial questionnaire produces a better approximation to reality than the second or any subsequent questioning.

This formal, "ask the experts" technique is obviously time consuming and depends to a great extent on the type of questions and how they are asked--a job for a psychologist.

Still, in a very non-formal way, most design engineers do "ask the experts" when there is uncertainty. That is, they ask their colleagues, and frequently look to the literature to find how others in their field have solved similar problems.

DECISION TREE or the decision flow diagram (Fishburn, 1964; Bellman, et.al., 1970; Tribus, 1969; Dantzig, 1963; Wagner, 1969; Raiffa, 1968; and Askren and Korkan, 1971) is, like the PERT chart, a visual comparative method. Unlike PERT it shows decision points rather than activities and is not based on time but rather on the natural progression of alternative decisions.

It appears straight-forward and logically sequential. Each decision alternative may be weighted, including values for human resources data, such as maintainability, repairability, manpower required, new technology necessary, etc. Askren (1971) has shown that such a system has acceptability at the systems engineering level, and has established a computer program for Design Option Decision Tree generation.

Such a decision analysis system appears to have all the requirements listed previously of an optimal design decision aid for the design engineer and is recommended as a reasonable method for use by the engineering designer.

Recommendations for future study. The use of Design Option Decision Trees should be attempted at the detail design phase and should include, at

each decision point room for "other alternatives", and new technology.

In addition, from the system, or subsystem point of view, it should include the possibility of feed-back loops, so that the effects of changes in alternatives "upstream or downstream" may be readily apparent.

METHOD	AREA IN WHICH GENERALLY USED	FORM OF INPUT	ANALYSIS METHOD	FORM OF OUTPUT	DEGREE OF DIFFICULTY (1)	PROBABILITY OF APPLICATION TO TRADE STUDIES (2)
P.E.R.T.	BUSINESS AND ENGINEERING MANAGEMENT	SEQUENTIAL (CPM)	VISUAL COMPARATIVE	FLOW DIAGRAM	2	0.1
MONTE CARLO	MARKETING INVENTORY TRAFFIC NUCLEAR	RANDOM PROBABILITY	ANALYTICAL MODEL	PROBABILITY	5	0.1
LINEAR PROGRAMMING	MANAGEMENT SYSTEMS CONSTRUCTION TRANSPORTATION	MATH EQUATIONS AND INEQUITIES	ANALYTICAL MODEL	OPTIMUM SOLUTION	7	0.3
DELPHI	ANY COSTLY UNCERTAINTY	QUESTIONAIRE TO EXPERTS	ITERATION	EXPERT OPINION (CONCENSUS)	7	0.3
DECISION TREE	PROBABILITY THEORY MILITARY	SEQUENTIAL (CPM)	VISUAL COMPARATIVE	FLOW DIAGRAM	2	0.9

TABLE III.F.1 EVALUATION OF DECISION THEORY METHODS

(1) BASED ON SCALE OF 0-10
(2) BASED ON SCALE OF 0-1.0

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Section IV.

Classic and Representative Examples of Engineering Design

In the study of the design process it is useful to describe some particular examples as guideposts to define the more general processes. One historical example is the experience of Wilbur and Orville Wright. They were the prototype of present-day aerospace designers in being thorough and systematic and in combining science and engineering for effective advance into new developments. They are also interesting in that the two did essentially all their own research, design, construction, test, and maintenance.

Additional examples which have been considered but not yet studied are the Northrop F-5, the Lockheed "skunk works", and the French government aircraft design groups.

Section IV·A.

Wilbur and Orville Wright, by Malcolm L. Ritchie

The design methods of Wilbur and Orville Wright are interesting to students of the design process from several different standpoints. One of these is that they were forerunners of the present day aerospace procedure in some very important respects. In particular they set the pattern for a combination of thorough engineering and the integral use of science. They were very systematic in their engineering design. They carefully went step by step to the point at which they realized that the data they were using were inadequate. At that point, they built a wind tunnel and produced basic aerodynamic data. When they had produced enough new knowledge to proceed, they returned to their design effort and carried it to conclusion.

Another aspect at which the experience of Wilbur and Orville is significant is that they began with very little formal education. Before 1900 there were no clues to foretell their final significant accomplishments. They began their work by themselves with almost no background at a time when other people in the world, particularly the French, were working with many well trained people, with support, with a great deal of motivation for solving the problem of flight. It was the French with their considerable amount of engineering and scientific interest in aviation who recognized the Wright contributions. When Wilbur made the first demonstration in France of their airplanes and their ability to fly them, the French made Wilbur and Orville famous overnight throughout the world. They were famous in their own home town of Dayton, Ohio only upon their return from France.

Another way to describe the importance of the experience of the Wright Brothers from the standpoint of design is to show the economy of effort that goes with efficient design procedures. This can be expressed in several ways. One way is to note that the accomplishments made by Wilbur and Orville were done without outside funding. Their equipment and efforts were built with their own money, modest profits from a bicycle repair and manufacturing business, and their own time and efforts. Almost all of their work was done by themselves. While they were doing this design and construction successfully, there were other workers receiving hundreds of thousands of dollars to try to solve a part of the problem. For example, Samuel P. Langley had the resources of the Smithsonian Institute behind him plus occasional fundings up to $50,000 to develop a flying machine. Even with this much in resources behind him and several years over which to exploit them, the only contribution that the Wright Brothers could count out of Langley's efforts was the social impetus from the realization that a serious and respected scholar believed that flight was possible. None of the results of his prodigious efforts were of enough accuracy and enough values to be of use to the Wright Brothers in solving the flight problems.

It took the Wright Brothers four and one-half years from the time they began serious interest in aviation until they made the world's first successful power flight. In that period of time they continued to run their bicycle repair and manufacturing business. This business was seasonal and allowed them to spend some time each year devoting themselves exclusively to the problems of flight (it also paid all the costs). They were both bachelors and did indeed devote 100% of their time to aviation in the off-season. They had a thoroughly compatible relationship and a minimum of time was lost in transferring ideas from mind to mind.

A further part of their unique situation was that they were thoroughly systematic in their procedures. They documented things as they went along. They were very painstaking in writing down what they had discovered and outlining what they needed to learn yet. Further in their unique adventures, they were thoroughly convinced that they needed to couple first hand experience in their various gliding and flying devices with their calculations of what was going on. They were able to relate very clearly their calculations of lift and drag and shifts of center of pressure to those things they felt while gliding. Their ability immediately to translate these ideas into ingenious mechanical structures. This ability was not limited only to aerodynamic structure but they were able also to design their own engine. They designed it together. Orville made the molds for the cast cylinder heads and Charley Taylor (shop mechanic) machined the crankshaft from a thick piece of armor plate. When they concluded from their tests that they had to build a wind tunnel, they were able to invent and build ingenious devices for straightening the airflow and for measuring very abcurately lift and drag. They also made the scale models which they tested.

On all of these points the historians of aviation agree over this period of time that the contributions of the Wright Brothers simply outclass by a large margin everybody else in the history of aviation. Indeed, one of the noted historians of aviation, Charles Gibb-Smith, writes his history criticizing other people frequently on the basis of what they lacked that the Wright Brothers had. For example, he indicates that Hardgrave, who first began flying box kites with considerable results in Australia, may have been able to accomplish a great deal more if he had had someone else to talk to in Australia. Similarily he criticizes both Langley and Maxim because they were "chauffer minded." By that he meant that they built machines and then hired somebody to go up and fly them. It was abundently clear to Gibb-Smith that they simply could not learn enough this way. It took too long to get back information by this secondary process given the fact that the variables involved in flight were so complex and the knowledge so sketchy at this particular time.

The Wright Brothers background was that of a high school education with algebra, geometry, trigonometry and physics. That was enough to allow them to read the technical literature they would meet later. In their pre-aviation background they had built a printing press which they used to print the newspaper which they also published and edited. They had started a bicycle sales and repair shop and later on began manufacturing their own brand of bicycles.

The first step in their serious aviation venture was to write the Smithsonian Institute to ask about literature on the engineering and scientific aspect of aviation. This letter was written in May, 1899. They got back several sets of papers which were published by the Smithsonian and reference to some books. One reference was a three-volume set of aeronautical annuals which had been edited and published by James Means. Another book was by Octave Chanute called Progress in Flying Machines, which had been printed in 1894 and which gave a very comprehensive survey of some seventy experimental ventures in attempting to fly. These had largely been done in the ten to fifteen years before 1894. Chanute not only showed pictures of large number of flying machines, but also described their experiments and what had been learned. Further, he classified the kind of things known and outlined the problems which still remained to be solved before flight could be done successfully. He indicated that the way to solve problems was to build gliders first and learn how to control flying machines. He pointed out clearly how useful had been the experiments of Otto Lelienthal in Germany in learning many aspects of control and of aerodynamics through the process of building gliders to certain specifications and making numerous flights himself to test them.

Chanute was convinced that the individual must get out and fly gliders himself in order to learn what the processes were. Even at age 60 he built some machines and did some flying himself, although he had some younger assistants to help and to do most of the actual flying. From this background, it was not surprising that he encouraged the Wright Brothers as soon as he discovered them to be serious and capable young men willing to go in his direction. He was a most enthusiastic motivator. He provided them a sounding board, references to the technical literature, and a forum for presenting their work and ideas to the scientific community. Technically, the Wright Brothers owed only one contribution clearly to Chanute. That was the construction of a biplane with the kind of trussing Chanute had used in his construction of railroad bridges, the Pratt truss.

What the Wright Brothers did is as follows:

1. Built a 5' kite to test lateral control.

2. glider number one to test lift and lateral control.

3. Wrote a paper on the advantages of flying from the prone position which appeared in a German periodical on aviation.

4. Wrote a paper on definition of angle of attach (which was called at that time angle of incidence.)

5. Built glider number two to test lift, lateral and longitudinal control.

6. Wrote a paper on lift, lateral and longitudinal control which was published in September 1901, and which has been the most often reprinted article in the history of aviation.

7. Built a wind tunnel to evaluate published data and to add to it. They did these basic experiments in 1901 and 1902.

8. Built glider number three to embody the data from their wind tunnel test. All their experimental data checked out.

9. Built their flyer in 1903 to embody all their data. The word "flyer" was used for them to indicate an aircraft or an airplane. (An aeroplane was for them a technical term which was distinguished from aero curve.)

10. Designed propellers from their own theory.

11. Design and built an engine to produce 8 horsepower at 180 lbs. weight which was better than any they could buy.

12. Their flyer not only flew, but their performance was with 5% of what they had predicted it would be. Their calculations were so good that not only were they not surprised when it flew, but would have been very much surprised had it not flown.

13. They started several successful flying training schools.

14. They began manufacturing airplanes and for a time were the most successful manufacturers based on their own data.

After they had built the first practical aircraft, they very quickly had to become industrial leaders in order to continue their old practices of supporting themselves by their own efforts. Their efforts switched to production and finance problems. Even before Wilbur's death in 1912 they had greatly slowed in time and contribution to design.

Section V.

Recommendations

This study effort began with a problem. It was noted that the cost of maintaining and supporting Air Force hardware is on the increase despite years of effort by human resources research people to provide information required to reduce such costs. From data derived in this study - interviews with various people from the Systems Program Offices, contractor personnel, and others who are part of the design team and trying to implement greater responsiveness to data about maintainability - it seems to be clear that designing for reduced support costs is clearly needed and clearly recognized as an objective. What is not yet clear is the best way to do it.

There are some significant points to be made in this regard. For example, in the design of the A-10 aircraft there has been made a deliberate effort to put the maintainability cost into the whole program as part of design criteria. The design criteria include a dollar figure for acquisition cost and a specific figure for the number of maintenance hours to be required per flying hour. This approach in the case of the A-10 appears to be successful and it provides one way of looking at the problem which will make the design more sensitive to the support cost.

Another major point which was the result of these investigations was that there is a recognition of the importance of the design function in incurring support costs in two specific activities within the Air Force. One of these activities is the incorporation of support people in the design team under the program of integrated logistics support. It is the intent of this program to provide the logistics input into early tradeoff studies so that the support factors can be recognized in every design tradeoff. The other activity is that of life-cycle costing. This program is aimed at making design tradeoffs in view of not only immediate acquisition costs but also of costs to be incurred over the total life-cycle of the equipment. This approach should provide the kind of attention to the support problems which it merits when the approach has been fully implemented in the Air Force design efforts. Several efforts are aimed at learning how to do it.

It was apparent in the work in this program that there needed to be more effective criteria for evaluation of Air Force hardware to reflect the human resources cost in the program. This is a part of the needed development in order to make integrated logistics support in life-cycle costing effective in the course of Air Force weapon system development. There are activities aimed at developing the mathematical tools for implementation, and there are in the Systems Program Offices reports generated which are stimulated by life-cycle cost requirements. It seems hard to overestimate the value to be gained by hastening the day when the implication of life-cycle costing affects every design tradeoff. This problem may seem to be one

which calls simply for management attention in the Air Force, but there are aspects which call for research and analysis. At some point the specific projections of life-cycle costs overlap with what we have called "the form of human resources data." More is needed on this area overlap to speed up life-cycle costing implementation in Air Force design efforts.

Additional research work is needed also in the following detailed areas:

A. Specifications and the Work Statement.

It has been shown that the work statement is critical to the design process. The stated requirements and the number and kind of specifications which are called out in the work statement are very important to design and cost. Further study is needed on how much to specify and how to write the criteria for successful project criteria.

B. The Reward Structure as Perceived by the Design Engineer.

It has been made clear that design engineers work not only to satisfy the formal requirements in the work statement but also to satisfy the perceived rewards in their own working situation. Additional work is needed to illuminate the degree to which these perceived rewards influence the end design.

C. Engineering Education.

It has been shown that what an engineer knows and what his design procedures amount to are likely influenced very importantly by the process by which he became an engineer. Additional information needs to be generated about the nature of engineering education and the kind of strengths and biases which appear in the perspective of the design engineer as a consequence.

D. An Overall Model of the Design Process.

It appears to be useful to bear in mind continually that engineering design is a complex process with all parts related to each other. A continuing effort to relate in some meaningful way the various elements of the process appears very useful. This effort will be that of constructing a model of the engineering design process which can show relative contributions of the many variables to the total design process.

SECTION VI.

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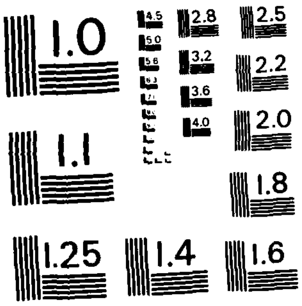

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